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# Therapeutic Benefits of a 16-Week Compassion Focused Therapy for Overeating Are Associated With Positive Autonomic Changes and Putamen Responses

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## ABSTRACT

**Objective:** Compassion Focused Therapy (CFT) has shown promise in reducing shame and self-criticism and enhancing compassion in individuals with eating difficulties. However, the neurophysiological mechanisms, particularly those related to learning, are not well understood. This longitudinal study investigated the neurophysiological effects of an online CFT for overeating (CFT-OE) using functional magnetic resonance imaging (fMRI) and heart rate variability (HRV).

**Method:** A total of 15 women seeking treatment for overeating completed a 16-session group-format CFT-OE program. At pre- and post-intervention, participants completed self-report psychological measures and underwent task-based fMRI with concurrent HRV recordings, in which they engaged in four emotion regulation conditions (avoidance, rumination, self-criticism and self-reassurance). A healthy control group ($n = 20$) was also recruited and completed a single fMRI scan and self-report psychological measures.

**Results:** Following the CFT-OE intervention, a reduction in eating disorder symptoms, self-criticism, rumination, and food thought suppression was observed, alongside improvements in self-reassurance and self-compassion. Participants also exhibited increased bilateral putamen activation during self-reassurance, showing normalization to a level comparable to controls, associated with reduced food thought suppression. Right putamen activation during self-criticism was associated with decreases in binge eating. Cortical activation decreased in several prefrontal areas, including the superior and middle frontal gyri. Correlation analysis showed that improvement in self-compassion engagement and action was associated with HRV changes, suggesting a positive modulation of the vagal system.

**Conclusions:** Results suggest that CFT-OE operates via subcortical mechanisms in the putamen, involved in habit learning, and reduces frontal cortical activity as individuals become more adept at using self-compassion strategies. This shift may reduce emotional reactivity, allowing participants to better manage distress, as reflected by improved vagal tone and decreased prefrontal activation.

## 1 | Introduction

Overeating, which involves consuming large amounts of food (Goldschmidt 2017), exists on a spectrum and does not necessarily indicate the presence of a clinical eating disorder. It can manifest in various forms, such as grazing (continuous consumption of small portions of food), emotional eating (using food to cope with painful emotions) and binge eating (perception of loss of control when overeating). Severe cases may meet the criteria for binge eating disorder (BED). Persistent and regular overeating is often linked to functional impairment, weight gain, and obesity (Ackard et al. 2003; Frayn and Knäuper 2018; Heriseanu et al. 2019; Herle et al. 2020; Masheb and Grilo 2006; Mitchison et al. 2018).

People who chronically overeat often struggle with regulating distressing emotions (Walenda et al. 2021) and may engage in cognitive strategies, such as rumination, thought suppression, and self-criticism, which maintain or exacerbate their eating difficulties (Cowdrey and Park 2012; Goss 2011; Rawal et al. 2010; Seidel et al. 2016). While these strategies aim to protect against perceived threats, they can reinforce difficult emotions like shame and guilt (Barnes et al. 2010; Dunkley and Grilo 2007; Erskine and Georgiou 2010; Gilbert and Irons 2005; Inzlicht and Schmeichel 2012; Lazarus and Shahar 2018; Mellings and Alden 2000; Michael et al. 2007; Nolen-Hoeksema 2000; Surrence et al. 2009; Verhaeghen et al. 2005).

In contrast, a compassionate response has been shown to help individuals cope with difficult emotions and foster positive affect (Förster and Kanske 2022; Inwood and Ferrari 2018). Compassion involves being sensitive to suffering and engaging in a motivational response to alleviate it (Gilbert et al. 2024). Compassion can be considered an emotion regulation strategy, requiring individuals to respond to distressing emotions with awareness, kindness, and warmth (Gilbert 2009b, 2014).

Compassion is linked to autonomic nervous system activity, particularly the vagus nerve, a major component of the parasympathetic nervous system that regulates heart rate (Petrocchi and Cheli 2019; Porges 2007). Compassionate responses are associated with increased heart rate variability (HRV; for a meta-analysis, see Di Bello et al. 2020; Kim et al. 2020b), reflecting enhanced parasympathetic regulation, which is linked to greater emotional regulation capacity (Williams et al. 2015), social engagement (Geisler et al. 2013), and feelings of calmness (Geisler et al. 2010). However, the relationship between HRV and compassion seems to be nonlinear; as HRV may decrease when empathizing with suffering but increase when performing helpful actions (Di Bello et al. 2021; Steffen et al. 2021).

Compassion Focused Therapy (CFT) aims to help individuals with high levels of self-criticism and shame (Gilbert 2009a) and has demonstrated promising results in the treatment of eating difficulties (Gale et al. 2014; Goss and Allan 2009; Haley et al. 2022; Kelly et al. 2017; Kelly and Carter 2015; Marques et al. 2024c; Williams et al. 2017). Additionally, CFT has been found to be beneficial for individuals with obesity experiencing body weight-related shame (Carter et al. 2023). A recent meta-analysis involving clinical and nonclinical samples further supports the efficacy of CFT in reducing negative psychological outcomes, such as depressive symptoms and self-criticism, while enhancing compassion toward oneself and others (Petrocchi et al. 2024). To date, no functional magnetic resonance imaging (fMRI) studies have yet investigated neural changes following a CFT program for eating-related difficulties. Moreover, research on the neural effects of compassion-based interventions in healthy or clinical populations is limited. For instance, Lutz et al. (2020) found increased activation in the anterior insula and prefrontal cortex in chronic pain patients following a brief self-compassion training. Ashar et al. (2021) observed heightened activation in the medial orbitofrontal cortex (mOFC) after a 4-week compassion meditation program delivered via a smartphone application for healthy adults. Klimecki et al. (2013) found that compassion training activated brain regions related to positive affect and affiliation, such as the mOFC, putamen, pallidum, and ventral tegmental area. In line with these findings, a meta-analysis of fMRI studies identified several key brain regions associated with compassion, including the middle frontal gyrus, bilateral inferior frontal gyrus, bilateral insula, anterior cingulate cortex, medial frontal gyrus, and basal ganglia/thalamus (Kim et al. 2020a).

Neuroimaging studies suggest that individuals struggling with emotion regulation show increased activity in limbic regions, such as the amygdala and insula, involved in emotional salience and integration of multimodal information. In contrast, they tend to show decreased activity in the prefrontal cortex (PFC), particularly the ventrolateral PFC and dorsolateral PFC (dlPFC; for a review, see Ochsner et al. 2012). The few neuroimaging studies involving individuals with obesity have also shown heightened activation in the right anterior insula and reduced activation in the ventromedial PFC during cognitive emotion regulation (Steward et al. 2016, 2019).

Thus, it is often thought that therapy strengthens prefrontal activation to regulate subcortical regions via top-down processes (Fournier and Price 2014; Ochsner et al. 2012). However, some studies have challenged this view, with authors proposing that the efficacy of the therapy would rather be expressed through bottom-up and/or subcortical mechanisms (Barnhofer et al. 2021; Kober et al. 2017, 2019; Smallwood et al. 2016; Westbrook et al. 2013).

There are no fMRI intervention studies for eating psychopathology, and hypothesis-driven studies of the mechanisms of action of the intervention are needed. This was made possible by a recent discovery highlighting that the putamen is a core region disrupted in binge eating disorder and bulimia nervosa (Wang et al. 2023). The putamen is a key region associated with learning and habit formation, with an important role in

**Summary**

- An online compassion focused therapy for overeating (CFT-OE) program was associated with improvements in clinical symptoms and changes in neurophysiological responses.
- After the program, participants showed increased activation in the putamen, a region involved in habit learning, and decreased activity in the prefrontal cortex, which may relate to improved emotion regulation.
- Key components of self-compassion—sensitivity to suffering and the motivation to alleviate it—were distinctively linked to heart rate variability.

reinforcement learning mechanisms involving reward and punishment processing (Delgado et al. 2003; Pagnoni et al. 2002; Yin and Knowlton 2006). Also, similar to what is observed in drug addiction, Moore et al. (2017) propose that compulsive overeating is related to aberrant reward learning mechanisms in the basal ganglia.

Given the interplay between physiological and neural mechanisms in compassion, a multimodal approach integrating HRV and task-based fMRI (instead of resting state-based approaches) provides a more comprehensive framework for understanding therapeutic effects. We aimed to investigate the mechanisms of action underlying an online 16-session Compassion-Focused Therapy for Overeating (CFT-OE) program. Participants underwent an fMRI task before and after the intervention to examine brain responses to different cognitive emotion regulation strategies, that is, avoidance, rumination, self-criticism, and self-reassurance (a proxy for self-compassion). A prior study evaluating the potential effectiveness of the CFT-OE found that after the program, participants reduced eating disorder symptoms, shame, and self-criticism, along with improvements in self-compassion (Marques et al. 2024c).

We hypothesized that neural changes underlying this intervention would occur in the basal ganglia, and in particular the putamen, as it is central to habit acquisition. By investigating putamen activation in the context of an emotion regulation task, we aimed to determine whether CFT-OE facilitates shifts in neural activity related to maladaptive regulatory habits. We also hypothesized that high-level cortical regions involved in emotion regulation might maintain or even decrease their activity. Furthermore, an additional group of healthy participants underwent a single fMRI scan for further comparison with individuals with overeating. We expected to observe differences in brain activation in the basal ganglia and prefrontal areas between the healthy controls and participants with overeating at pre-intervention. However, at post-intervention, participants with overeating would show brain activation patterns similar to healthy control individuals, indicating the intervention's effectiveness in normalizing activity within these brain regions.

During the fMRI task, HRV was measured to assess autonomic responses. Additionally, participants completed self-reported measures related to eating psychopathology, thought suppression (avoidance), rumination, self-criticism, self-reassurance, and self-compassion. An earlier work using this fMRI task in healthy individuals showed that irrespective of levels of activity, activation patterns were distinct across these strategies (Marques et al. 2024d), providing a basis to investigate the neural effects of the online CFT-OE program.

## 2 | Method

### 2.1 | Participants and Recruitment

A total of 15 females seeking treatment for overeating (mean age = 32.73; SD = 9.96) enrolled in a 16-week group CFT-OE program. Their mean body mass index (BMI) was 40.96 (SD = 4.80), which falls in the obesity category according to the World Health Organization (2010). All participants were right-handed.

Recruitment occurred in public outpatient treatment services (weight management and psychology) in Portugal. Participants provided written informed consent, and the study was approved by the Ethics Committee of the Coimbra Hospital and University Centre.

Participants completed an online screening assessment with a trained clinical researcher to determine their eligibility for the study. Eligibility criteria included being female, at least 18 years old, BMI ≥ 25 kg/m$^2$, presence of overeating, and having internet access and a computer with a camera. Overeating was assessed using the BED section of the Structured Clinical Interview for DSM-5 (SCID-5-RV; First et al. 2015) and questions on eating patterns and grazing habits. The presence of overeating was met if participants showed grazing, chaotic eating patterns (i.e., irregular and inconsistent eating behaviors, such as skipping meals, unpredictable meal times, no structured eating routine), emotional eating, or binge eating with clinical impairment. Excluded criteria included sustained compensatory behaviors, active suicide risk, self-harm, severe psychiatric condition, medical condition or procedure that may affect eating (e.g., diabetes, history of bariatric surgery), current alcohol/drug abuse, contraindications to MRI, or receiving current psychological treatment for overeating.

A total of 20 healthy control females (mean age = 28.40; SD = 7.80; mean BMI = 22.95; SD = 3.18) with no current or past psychiatric disorders (including an eating disorder) were recruited through advertisements and word-of-mouth.

### 2.2 | Procedures

CFT-OE participants underwent MRI scans at pre- and post-intervention in ICNAS, University of Coimbra. CFT-OE participants completed self-report measures on both time points related to eating psychopathology and cognitive strategies. These included the Binge Eating Scale (BES; Gormally et al. 1982; Portuguese version: Duarte et al. 2015), Three-Factor Eating Questionnaire-R21 (TFEQ-R21; Cappelleri et al. 2009; Portuguese version: Duarte et al. 2020), Eating Disorder Examination Questionnaire (EDE-Q; Fairburn and Beglin 1994; Portuguese version: Machado et al. 2014), Food

Thought Suppression Inventory (FTSI; Barnes et al. 2010; Portuguese version: Marques et al. 2024b), Ruminative Response Scale for Eating Disorders (RRS-ED; Cowdrey and Park 2011; Portuguese version: Marques et al. 2024a), Forms of Self-Criticizing/Attacking and Self-Reassuring Scale (FSCRS; Gilbert et al. 2004; Portuguese version: Castilho et al. 2015b), Self-Compassion Scale-Short Form (SCS-SF; Raes et al. 2011; Portuguese version: Castilho et al. 2015a), and Compassionate Engagement and Action Scales (CEAS; Gilbert et al. 2017). Furthermore, to assess grazing behavior, participants were asked, "How frequently do you graze on food during the day?" with the following response options: never, once a day, 2 to 3 times a day, or more than 3 times a day. Eating patterns were evaluated with the question, "How many meals do you have per day?". Binge eating episodes were assessed using two questions from the EDE-Q: "Over the past 28 days, how many times have you eaten what other people would regards as an unusually large amount of food (given the circumstances)?" and "... On how many of these times did you have a sense of having lost control over your eating (at the time you were eating)?"

The healthy control group underwent a single MRI scan and completed only the measures directly related to the emotion regulation strategies involved in the fMRI task, including the FTSI, RRS-ED, FSCRS, SCS-SF, as well as EDE-Q.

### 2.3 | Compassion Focused Therapy for Overeating (CFT-OE) Program

Participants attended weekly 2-h online CFT-OE sessions for 16 weeks in a group format. All sessions were administered by two licensed clinical psychologists, with previous training in CFT, supervised by a consultant clinical psychologist (KG) who developed CFT for eating disorders. The program, delivered via Zoom, introduced the evolutionary perspective of the human mind and how eating disorder symptoms can be understood using a compassionate mind formulation. Participants were introduced to soothing and compassion exercises to practice in and between sessions. Regular eating and meal planning were also addressed throughout the CFT-OE. Participants were required to attend a minimum of eight sessions to be included in the study. A more detailed explanation of the CFT-OE intervention program, including the sessions' content, can be found elsewhere (Marques et al. 2024c).

### 2.4 | fMRI Paradigm

During the fMRI scanning, participants performed a paradigm related to cognitive strategies (described in detail in Marques et al. 2024d). After a 15-s baseline (presentation of a fixation cross), participants were presented with a 4-s audio file representing one of four cognitive strategies related to eating and body concerns, such as avoidance (e.g., "I'll think of good things"), rumination (e.g., "Why I have this body?"), self-criticism (e.g., "I don't like my body!") and self-reassurance (e.g., "It's not my fault for having the body I have"). Participants were then instructed to repeat the sentence and engage with the strategy for 26 s while viewing an image of food or body presented on the screen. After the engagement task, participants selected their predominant emotion, within 5 s, among five possible options (sad, anxious, ashamed, angry, and calm) and rated their performance in the engagement task, within 5 s, using a scale with 4 levels ("I did it without difficulty", "I did it with little difficulty", "I did it with great difficulty" and "I could not do it").

### 2.5 | MRI Data Acquisition and Pre-Processing

MRI data were obtained using a 3T Siemens Prisma$^{fit}$ scanner with a 64-channel receive head coil. High-resolution T1-weighted images (TR = 2500 ms, TE = 2.15 ms, flip angle = 8°, FOV = 256 mm, 192 slices, voxel size = 1 × 1 × 1 mm) were obtained. Functional data were obtained using a T2*-weighted multiband EPI pulse sequence with an acceleration factor of 6 (TR = 1000 ms, TE = 37 ms, flip angle = 52°, FOV = 200 mm, 72 slices, slice thickness = 2 mm, voxel size = 2 × 2 × 2 mm). Spin echo field maps for each participant were also acquired, with the following parameters: TR = 8000 ms, TE = 66 ms, flip angle = 90°, FoV = 200 mm, 72 slices with a slice thickness of 2 mm.

FMRI data pre-processing was carried out using *fMRIPrep* 20.2.1 (Esteban et al. 2018a; RRID:SCR_016216; Esteban et al. 2018b), which is based on *Nipype* 1.5.1 (Gorgolewski et al. 2011, 2018; RRID:SCR_002502). For step-by-step detailed information, see Marques et al. (2024d).

### 2.6 | Pulse Rate Variability (PRV) Data Acquisition and Pre-Processing

In fMRI studies, obtaining HRV indices is frequently more practical by recording photoplethysmogram (PPG) data due to the interference caused by strong electromagnetic fields on electrocardiogram recordings (Felblinger et al. 1999). Thus, PRV was used as a reliable proxy for HRV (Schäfer and Vagedes 2013). PPG was acquired simultaneously with fMRI using a pulse finger sensor connected to the MRI scanner's Physiological Measurement Unit. The PPG was sampled at 200 Hz, except for the second visit of seven participants, where the sampling rate was 400 Hz.

PPG signals from each participant were pre-processed by applying a 6th-order Butterworth bandpass filter (0.5–20 Hz) to remove baseline drift and unrelated higher-frequency components, then down-sampled to 36 Hz. After pre-processing, signals were visually inspected for distortions that could compromise analysis, resulting in the exclusion of two participants whose signals were substantially buried in noise to identify pulse peaks.

The cleaned PPG signal was used to compute PRV by first identifying the pulse peaks, subsequently computing interbeat intervals (IBIs), and finally using a cubic spline interpolation to obtain a uniformly sampled time series—a step recommended for frequency domain analysis of PRV (Peltola 2012).

To extract time and frequency domain markers, the PPG and PRV signals were segmented according to each cognitive strategy onset (26 s). To allow for the normalization of metrics, we extracted segments from the baselines preceding each event (15 s).

For their documented relationship with the parasympathetic nervous system and the vagal tone contribution to the PRV (Di Bello et al. 2020), the root mean square of the differences between successive IBIs (RMSSD) and relative power in the high-frequency (HF) band of the PRV (Shaffer and Ginsberg 2017; Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996) were extracted from each of the segments. To better isolate the effect of the cognitive strategy on physiological responses from other variables and allow for posterior group analysis, each metric was normalized by subtracting the baseline value from the condition segment value. Thus, we ended up with values that translate to variations in relation to the baseline, instead of absolute values. For group analysis, metric values were averaged per strategy, visit, and participant.

All pre-processing and feature extraction algorithms were implemented in MATLAB (R2023b, MathWorks, USA).

### 2.7 | MRI Data Processing and Statistical Analyses

Image processing was conducted in Statistical Parametric Mapping software (SPM 12). Data were high-pass filtered using a cut-off frequency of 0.007 Hz and spatially smoothed with a Gaussian kernel of FWHM = 4 mm. To test whether activation in brain areas would change with the CFT-OE, contrasts of interest (post-intervention > pre-intervention) were calculated for avoidance, rumination, self-criticism, and self-reassurance. Our main hypothesis was of positive changes in the putamen as a region within habit-learning circuits in the basal ganglia. However, we also used a within-subject design to undergo an exploratory study of other regions. In our Random Effects Analysis, we applied a voxel threshold of $p < 0.001$, cluster corrected for 10 or more continuous voxels, which allowed us to also address activity patterns in other brain regions instead of defining only a priori region of interest (ROI) in the putamen. Neuroanatomical labeling was performed through the AAL3 (Rolls et al. 2020). All coordinates were reported in MNI space.

To test whether CT-OE participants at pre- and post-intervention would differ significantly from healthy controls, frontal areas and basal ganglia ROIs were defined based on significant clusters of activation identified in the post-intervention > pre-intervention contrasts for each condition. The SPM MarsBaR toolbox was used to define ROIs in each condition and extract all beta values of each ROI. *T*-tests were conducted to examine differences in beta values within each ROI, comparing healthy controls with CT-OE participants at pre- and post-intervention.

Linear mixed models (LMM) were computed with R software (*lme4* package; Bates et al. 2015) to examine changes in self-report measures from pre- to post-intervention. Of note, participants completed questionnaires at the 3-month follow-up; thus, LMM were calculated using the three time points. Given that participants underwent an fMRI scan only at pre- and post-intervention, we presented the results for these two time periods. Effect sizes were calculated using Cohen's *d* and interpreted according to Cohen (1988): 0.2 for small, 0.5 for moderate, and 0.8 for large. Differences in eating behaviors between pre- and post-intervention for CFT-OE participants were analyzed using the Sign test or the Wilcoxon signed-rank test.

Comparisons of proportions for emotional and performance ratings in each condition, between pre- and post-intervention, were also conducted, providing a 95% confidence interval (CI) for the difference between proportions. Changes in brain activations, HRV measures, and self-report psychological measures were calculated (Δ = post-intervention value minus pre-intervention value), with Spearman rank-order correlations used to assess associations between them, considering significance at $p < 0.05$.

## 3 | Results

### 3.1 | Effects of CFT-OE on Clinical Symptoms

A total of 18 participants enrolled in the program. During the intervention, three participants dropped out due to work schedule conflicts, resulting in an attrition rate of 16.7%. All 15 remaining participants completed the assessments at pre-intervention, post-intervention, and the 3-month follow-up, achieving a 100% completion rate. All met the minimum attendance requirement for inclusion, with an average attendance of 14 out of 16 sessions (SD = 2.24).

Table 1 presents Cronbach's alpha values, and differences in pre- and post-intervention scores for the measures in the study, confidence intervals, and effect sizes. Accordingly, at post-intervention, participants reported significant decreases in binge eating, uncontrolled eating, emotional eating, and eating psychopathology, food thought suppression, rumination, and self-criticism. In contrast, participants showed a significant increase in cognitive restraint, self-reassurance, and self-compassion. Effect sizes of significant changes from pre- to post-intervention were moderate to large.

After the intervention, participants showed a significant reduction in grazing behaviors and loss of control over eating, while adopting more structured eating patterns. Supplementary Table S1 provides the comparisons of eating behaviors between pre- and post-intervention.

### 3.2 | Effects of CFT-OE on Behavioral Ratings During the fMRI Task

After the engagement task (assimilating the sentence content while appraising an image of food or body), participants identified the elicited emotion and rated their performance. Table 2 presents the percentages of emotion and performance ratings for each condition at pre- and post-intervention.

Post-intervention ratings of sadness, anxiety, shame, and anger decreased across all conditions, except for sadness in rumination and shame in avoidance. Conversely, calmness increased in all conditions. Notably, sadness ratings for self-reassurance showed

**TABLE 1** | Pre- and post-intervention scores on self-report measures ($N = 15$).

| | α | Assessment time<br>Pre-intervention<br>*M* (SD) | Post-intervention<br>*M* (SD) | Adjustment difference<br>Pre-post<br>Estimate [95% CI] | d |
|---|---|---|---|---|---|
| Relationship with food | | | | | |
| BES | 0.81 | 24.53 (6.93) | 14.07 (7.20) | −10.47 [−14.88, −6.06] | −1.75 |
| TFEQ-R21 | | | | | |
| Cognitive restraint | 0.66 | 12.00 (2.27) | 13.93 (3.63) | 1.93 [0.44, 3.43] | 0.96 |
| Uncontrolled eating | 0.90 | 26.00 (6.01) | 22.13 (6.09) | −3.87[−6.52, −1.22] | −1.08 |
| Emotional eating | 0.95 | 19.73 (4.59) | 16.67 (4.34) | −3.07 [−5.16, −0.98] | −1.08 |
| EDE-Q | 0.84 | 2.87 (0.85) | 2.10 (0.98) | −0.77 [−1.16, −0.38] | −1.46 |
| Avoidance | | | | | |
| FTSI | 0.95 | 35.53 (11.89) | 30.07 (12.95) | −5.47 [−9.41, −1.52] | −1.03 |
| Rumination | | | | | |
| RRS-ED | 0.79 | 22.47 (4.73) | 18.67 (5.86) | −3.80 [−6.72, −0.88] | −0.96 |
| Self-criticism and self-reassurance | | | | | |
| FSCRS Inadequate self | 0.92 | 2.33 (0.98) | 1.71 (0.90) | −0.61 [−0.96, −0.27] | −1.33 |
| FSCRS Hated self | 0.62 | 1.39 (0.73) | 0.83 (0.61) | −0.56 [−0.87, −0.25] | −1.33 |
| FSCRS Reassured self | 0.90 | 1.57 (0.85) | 1.94 (0.93) | 0.38 [0.08, 0.67] | 0.95 |
| Self-compassion | | | | | |
| SCS-SF | 0.94 | 30.07 (9.79) | 37.33 (9.19) | 7.27 [2.89, 11.64] | 1.23 |
| CEAS SC Engagement | 0.70 | 28.53 (7.37) | 20.67 (7.04) | 4.07 [−0.67, 8.80] | 0.64 |
| CEAS SC Action | 0.84 | 19.47 (5.88) | 20.67 (7.04) | 1.20 [−3.09, 5.49] | 0.21 |

*Note:* The Cronbach's alpha values presented correspond to the baseline measures.
Abbreviations: BES, Binge Eating Scale; CEAS SC, Compassion Engagement and Action Scales, Self-Compassion; EDE-Q, Eating Disorder Examination Questionnaire; FSCRS, The Forms of Self-Criticizing/Attacking and Self-Reassuring Scale; FTSI, Food Thought Suppression Inventory; RRS-ED, Ruminative Response Scale for Eating Disorders; SCS-SF, Self-Compassion Scale – Short Form; TFEQ-R21, Three-Factor Eating Questionnaire-R21.

a significant decrease from pre- to post-intervention, and calmness ratings significantly increased across all conditions.

Performance ratings also improved, with participants reporting reduced difficulty in completing the task, particularly for self-reassurance. The proportion of "I did it without difficulty" significantly increased for avoidance and self-reassurance. Significant changes were also observed in the "I did it with little difficulty" rating for avoidance and in the "I did it with great difficulty" and "I could not do it" ratings for self-reassurance.

## 3.3 | Effects of CFT-OE on Neural Responses During the fMRI Task

Although we were mainly interested in the responses in the basal ganglia regions, particularly the putamen, we also examined whole-brain activation patterns. Comparing pre- and post-intervention brain responses (post vs. pre contrast, Table 3; Figure 1), we found differential activation in the left superior occipital gyrus for the avoidance condition. For self-criticism, activation increased in the right putamen, fusiform gyrus, and hippocampus. Self-reassurance showed heightened bilateral putamen activation, extending into the left amygdala. No significant increases were observed for rumination. Notably, participants exhibited decreased PFC activity (dlPFC, middle, and inferior frontal gyrus) across all conditions. For self-reassurance, reduced activation was also observed in bilateral crus I and superior temporal gyrus, extending into the insula.

## 3.4 | Correlational Analyses Between Changes in Brain Activation and Psychological Measures

Supplementary Table 2 reports correlations between changes in brain activity and psychological measures. Increased putamen activity during self-criticism was significantly associated with a decrease (i.e., improvement) in BES scores ($r = -59$). Bilateral putamen activation during self-reassurance correlated with a reduction in FTSI, $r = -0.54$ to $-0.58$ (see Figure 1). Changes in the middle frontal gyrus activation during rumination were positively linked to reduced RRS-ED scores ($r = 0.53$), while

**TABLE 2** | Percentages of emotion and performance ratings for each condition.

| | Self-criticism | | | Avoidance | | | Rumination | | | Self-reassurance | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % Pre | % Post | 95% CI for difference | % Pre | % Post | 95% CI for difference | % Pre | % Post | 95% CI for difference | % Pre | % Post | 95% CI for difference |
| **Emotion** | | | | | | | | | | | | |
| Sad | 25.34 | 21.83 | [−0.07, 0.14] | 22.60 | 13.38 | [−0.01,0.19] | 22.60 | 24.65 | [−0.13, 0.08] | 32.19 | 17.61 | [0.04, 0.25] |
| Anxious | 17.81 | 14.79 | [−0.06, 0.12] | 23.29 | 15.49 | [−0.02, 0.18] | 19.18 | 14.79 | [−0.05, 0.14] | 11.64 | 6.34 | [−0.02, 0.13] |
| Ashamed | 20.55 | 14.08 | [−0.03, 0.16] | 11.64 | 16.20 | [−0.13, 0.04] | 16.44 | 12.68 | [−0.06, 0.13] | 7.53 | 5.63 | [−0.05, 0.08] |
| Angry | 14.38 | 10.56 | [−0.04, 0.12] | 12.33 | 7.75 | [−0.03, 0.12] | 21.92 | 14.79 | [−0.02, 0.17] | 15.75 | 9.15 | [−0.02, 0.15] |
| Calm | 21.92 | 38.73 | [−0.28, −0.06] | 30.14 | 47.18 | [−0.29, −0.05] | 19.86 | 33.10 | [−0.24, −0.02] | 32.88 | 61.27 | [−0.40, −0.17] |
| **Performance** | | | | | | | | | | | | |
| I did it without difficulty | 76.71 | 82.39 | [−0.16, 0.04] | 71.92 | 83.10 | [−0.21, −0.01] | 76.71 | 80.28 | [−0.14, 0.07] | 50.00 | 77.46 | [−0.39, −0.16] |
| I did it with little difficulty | 17.81 | 9.86 | [−0.01, 0.17] | 19.86 | 8.45 | [0.03, 0.20] | 18.49 | 11.97 | [−0.02, 0.15] | 16.44 | 9.86 | [−0.02, 0.15] |
| I did it with great difficulty | 3.42 | 5.63 | [−0.08, 0.03] | 4.11 | 6.34 | [−0.08, 0.04] | 2.05 | 6.34 | [−0.10, 0.01] | 11.64 | 4.23 | [0.01, 0.14] |
| I could not do it | 2.05 | 2.11 | [−0.03, 0.03] | 4.11 | 2.11 | [−0.03, 0.07] | 2.74 | 1.41 | [−0.03, 0.05] | 21.92 | 8.45 | [0.05, 0.22] |

**TABLE 3** | Brain areas showing significant activation changes from pre- to post-intervention (contrast post > pre).

| Contrast/Region | k | x | y | z | t |
|---|---|---|---|---|---|
| **Avoidance** | | | | | |
| Superior occipital gyrus L | 13 | −14 | −78 | 44 | 5.44 |
| Middle frontal gyrus R (BA9) | 10 | 42 | 26 | 36 | −6.15 |
| Middle occipital gyrus L (BA19) | 11 | −44 | −84 | 2 | −4.68 |
| **Rumination** | | | | | |
| Middle frontal gyrus R (BA9) | 17 | 44 | 38 | 36 | −6.53 |
| Supplementary motor area L | 11 | 2 | 22 | 48 | −6.32 |
| **Self-criticism** | | | | | |
| Putamen R | 29 | 30 | 4 | −6 | 6.91 |
| | | 32 | −4 | −4 | 4.12 |
| Fusiform gyrus R/Parahippocampal gyrus R | 18 | 26 | −34 | −20 | 5.57 |
| Hippocampus R | 10 | 30 | −36 | −2 | 5.48 |
| Inferior frontal gyrus, opercular part R (BA9) | 13 | 56 | 14 | 34 | −6.20 |
| Middle frontal gyrus R/Superior frontal gyrus, dorsolateral R | 17 | 38 | −2 | 66 | −4.82 |
| **Self-reassurance** | | | | | |
| Putamen R | 16 | 24 | 2 | −8 | 6.74 |
| Putamen L/Amygdala L | 16 | −22 | 0 | −12 | 6.26 |
| Crus I of cerebellar hemisphere L | 13 | −44 | −66 | −22 | −7.42 |
| Superior temporal gyrus R (BA22)/ Insula R | 14 | 46 | −10 | −2 | −6.44 |
| Superior frontal gyrus, medial R (BA9) | 14 | 10 | 58 | 32 | −5.96 |
| Temporal pole: superior temporal gyrus R (BA38) | 10 | 56 | 10 | −16 | −5.78 |
| Crus I of cerebellar hemisphere R | 10 | 50 | −64 | −34 | −5.66 |
| Superior frontal gyrus, dorsolateral L | 13 | −22 | 62 | 8 | −5.65 |
| Superior frontal gyrus, dorsolateral R | 14 | 26 | 60 | 14 | −4.91 |
| | | 20 | 62 | 8 | −4.66 |

*Note:* Multiple clusters with the same label are shown in subsequent lines. Regions are labeled according to the AAL3 atlas. Peak MNI coordinates are reported.
Abbreviations: BA, Brodmann area; *L*, left; *R*, right.

supplementary motor area changes during rumination were positively correlated with uncontrolled eating ($r = 0.56$), but negatively with reassured self ($r = -0.58$). Changes in left Crus I during self-reassurance were positively associated with EDE-Q ($r = 0.55$), RRS-ED ($r = 0.83$), inadequate self ($r = 0.74$) and negatively with self-compassion ($r = -0.60$). All these correlations are suggestive of congruent relationships between changes in brain activity and clinical improvement.

### 3.5 | Putamen and Prefrontal Areas Differences Between Healthy Controls and CFT-OE Participants

At pre-intervention, significant differences in putamen activation were found between healthy controls and CFT-OE participants during self-criticism and self-reassurance. However, post-intervention, no significant differences were observed, consistent with activity normalization (see Table 4).

Differences between healthy controls and CFT-OE participants in identified ROIs for prefrontal areas are reported in Supplementary Table 3. At pre-intervention, we found significant differences in the majority of prefrontal ROIs for each condition. Nonetheless, at post-intervention, almost no statistically significant differences were found between both groups for these ROIs, also consistent with activity normalization.

The comparison of self-report measures between CFT-OE participants and the healthy control group is also presented in Supplementary Table 4. Overall, all pre-intervention measures in the CFT-OE group differed significantly from those of the healthy control group. However, the CFT-OE group at post-intervention no longer showed significant differences from the healthy control group in self-criticism and self-compassion.

### 3.6 | Correlations Between Changes in HRV and Psychological Measures

Changes in RMSSD-HRV during avoidance were negatively correlated with reassured self ($r = -0.58$, $p = 0.038$). Furthermore, HF-HRV changes during avoidance were negatively correlated with reassured self ($r = -0.77$, $p = 0.002$), self-compassion ($r = -0.57$, $p = 0.044$) and self-compassion engagement ($r = -0.69$, $p = 0.009$). In contrast, HF-HRV changes during rumination were positively correlated with reassured self ($r = 0.56$, $p = 0.046$) and self-compassion action ($r = 0.74$, $p = 0.004$). Changes in HF-HRV during self-reassurance were negatively correlated with self-compassion ($r = -0.55$, $p = 0.050$).

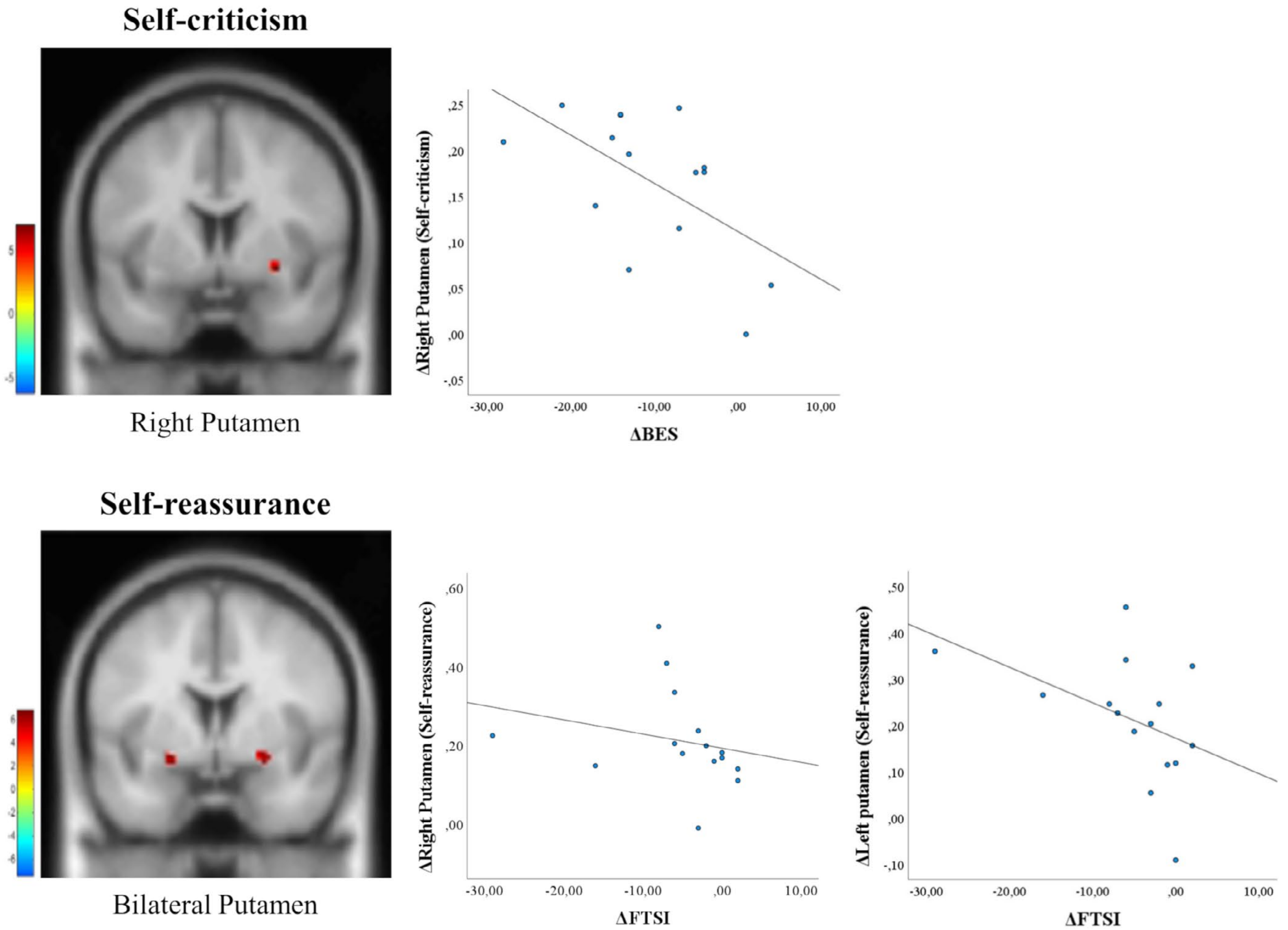


**FIGURE 1** | Changes in putamen activity after CFT-OE program (contrast post-treatment > pre-treatment) for self-criticism and self-reassurance and scatterplots depicting significant correlations between changes in putamen activity and self-reported measures. Scatterplot for self-criticism depicts a significant and negative correlation between Binge Eating Scale change (ΔBES) and right putamen activity change. Scatterplot for self-reassurance depict significant and negative correlations between Food Thought Suppression Inventory change (ΔFTSI) and bilateral putamen activity change.

## 4 | Discussion

The current study sought to investigate the neural and physiological mechanisms underlying a 16-week online CFT-OE program, focusing on HRV and task-based fMRI. In particular, we aimed to probe a recent hypothesis suggesting an important role of the putamen in humans with binge eating disorder and bulimia nervosa, a core region in habit-learning circuits within the basal ganglia (Wang et al. 2023).

Self-reported psychological measures showed significant improvements after the intervention, including reduced levels of eating psychopathology (except for cognitive restraint), self-criticism, rumination, and food thought suppression, along with increased levels of self-reassurance and self-compassion.

At the neural level, after the intervention, a larger activation of the putamen was observed when participants engaged in a self-critical dialog. This increased activation was associated with a clinically relevant reduction in binge eating, which highlights the role of reinforcement learning and improved recruitment of the reward dopaminergic circuitry. This is also consistent with the report by Wang et al. (2023), suggesting decreased basal dopamine D2/3 receptor binding potential in the striatum, and with shown microstructural changes and dopamine neurotransmission mediating habit learning in animal models. This result is also in line with the findings of a previous study, showing that the activation of reward circuitry in obese individuals with BED was inversely related to binge eating severity (Balodis et al. 2014).

An increase in putamen activation during self-reassurance was also observed. A self-reassuring dialog promotes positive affect and feelings of affiliation (Klimecki et al. 2013), acting as a form of self-reward and an additional reinforcement learning mechanism. Correlational analyses showed that higher bilateral putamen activation in self-reassurance was associated with reduced food thought suppression, further indicating clinical improvement. Thus, in the context of an emotion regulation task after compassion training, altered putamen activation may reflect shifts in how individuals engage with distress-related cues, based on emotionally driven reward signals and improved habit acquisition. The observed changes in putamen activity suggest that CFT-OE may facilitate the development and implementation of new, more adaptive regulatory habits.

**TABLE 4** | Differences in the putamen between healthy controls and CFT-OE participants at pre- and post-intervention.

| Condition/Region | Healthy controls versus pre-intervention | | Healthy controls versus post-intervention | |
|---|---|---|---|---|
| | *t* | *d* [95% CI] | *t* | *d* [95% CI] |
| **Self-criticism** | | | | |
| Putamen R | 3.12 | 1.00 [0.28, 1.70] | −2.10 | −0.68 [−1.36, 0.02] |
| **Self-reassurance** | | | | |
| Putamen R | 4.48 | 1.42 [0.66, 2.16] | −1.54 | −0.53 [−1.20, 0.16] |
| Putamen L/Amygdala L | 2.78 | 0.95 [0.24, 1.65] | −1.57 | −0.54 [−1.21, 0.15] |

*Note:* Regions are labeled according to the AAL3 atlas. Peak MNI coordinates are reported.
Abbreviations: *L*, left; *R*, right.

After the CFT-OE program, participants exhibited less activity in frontal regions (right middle, inferior and superior frontal gyrus/dlPFC) across all conditions. The effects of psychotherapy on prefrontal areas have been inconsistently reported in efficacy studies. It is worth noticing, however, that none of these studies were with people with eating and weight difficulties. While some studies show an increase in frontal areas after intervention as an indicator of successful emotion regulation (Jensen et al. 2012; Lutz et al. 2020), other studies show opposite findings (Klumpp et al. 2013; Månsson et al. 2013; Paquette et al. 2003). Also, recent neuroimaging work showed that strategies focused on noticing and accepting distressed feelings and promoting a conscious response to them may not depend on the recruitment of prefrontal areas related to cognitive control (Barnhofer et al. 2021; Kober et al. 2017, 2019; Smallwood et al. 2016; Westbrook et al. 2013). Given that CFT-OE is a program designed to cultivate a compassionate, understanding, and non-judgmental approach to suffering, it helps participants identify, tolerate, and experience difficult emotions without reacting to them, leading to reduced reactivity and negative emotional responses. Such changes may reflect decreased neural activity in areas linked to processing negative stimuli and cognitive control (particularly in frontal regions) and increased recruitment of habit learning regions due to the repeated practice of emotion regulation strategies promoted by the program.

The significant differences observed between healthy controls and CFT-OE participants at pre-intervention within defined ROIs underscore the presence of distinct neural activation patterns in both groups. However, these differences were absent at post-intervention, suggesting normalization of neural activation patterns, particularly in the putamen and prefrontal areas.

Exploratory correlational analyses between changes in HRV and self-reported reassured self and self-compassion suggested that behavioral changes were associated with a complex nonlinear pattern of autonomic responses. These findings are consistent with a previous study (Di Bello et al. 2021) that also used the CEAS scale to assess the two fundamental components of compassion: engagement (sensitivity to suffering) and action (motivation to alleviate the suffering). In line with the hypothesis drawn from that previous study, our findings suggest that higher sensitivity and engagement with suffering, which is trained in the program, may induce higher awareness and salience of the painful emotional experience, thereby resulting in a reduction in HRV as an index of augmented vagal tone. However, when individuals report an enhanced compassionate motivation to alleviate that suffering (self-compassion action), this can activate vagal tone, increasing HRV.

Taken together, results suggest that CFT-OE effectively regulates emotional states through subcortical learning mechanisms. Individuals learn to be more non-judgmentally aware of their internal experiences without automatically reacting to them, abstaining from engaging in elaboration or suppression of negative stimuli. Rather, individuals choose to employ a self-reassuring dialog to help them feel safe and soothe in response to distressing thoughts, emotions, or sensations. Furthermore, participants reported increased calmness at post-intervention, across all conditions, which supports the idea that compassion training fosters positive affect (Klimecki et al. 2013), self-soothing abilities, and emotion regulation in individuals with overeating (Gilbert and Procter 2006; Goss 2011; Goss and Haynes 2022).

The current study has some limitations that need to be addressed. The relatively small sample size reduces the statistical power of the study, which is typical of an interventional clinical pilot study. We already had a normative database (Marques, Sayal, et al. 2024d) and a record of a control group, but future studies might benefit from additional clinical control groups (participants with obesity without overeating). Future studies, such as randomized controlled trials, with larger samples and follow-up assessments should further investigate the unique processes by which self-compassion operates in individuals with overeating. Further replication studies with larger samples are warranted to draw conclusions regarding HRV.

Notwithstanding these limitations, this study provides novel insights into the neural and autonomic mechanisms underlying an online CFT intervention for individuals with overeating. It aligns with Wang et al. (2023) hypothesis about the putamen's role in human habit neural circuitry in eating disorders and provides further support for this hypothesis through a causal interventional approach. Our results indicate that the potential benefits of CFT-OE may operate through subcortical reinforcement learning mechanisms, promoting adaptive regulatory processes at both physiological and neural levels. This lays the groundwork for future research to improve the current understanding of the neural pathways underlying the effects of CFT.

### Author Contributions

**Cristiana C. Marques:** conceptualization, formal analysis, investigation, methodology, visualization, writing – original draft. **Alexandre Sayal:** formal analysis, investigation, methodology, writing – review and editing. **Lara Palmeira:** investigation, validation, writing – review and editing. **Kenneth Goss:** investigation, supervision, validation, writing – review and editing. **Rita Correia:** formal analysis, methodology, validation, writing – review and editing. **Paula Castilho:** investigation, project administration, supervision, writing – review and editing. **Ana T. Pereira:** investigation, supervision, writing – review and editing. **Miguel Castelo-Branco:** conceptualization, data curation, funding acquisition, investigation, project administration, supervision, writing – review and editing.


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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that supports the findings of this study are available on reasonable request from the corresponding author.

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### Supporting Information

Additional supporting information can be found online in the Supporting Information section.