The effect of an active-controlled 8-week Mindful Eating intervention on food-related attentional control

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Abstract:
Background: Attentional control is needed to overcome an attentional bias towards food cues. Overcoming this bias is important in avoiding unhealthy eating behaviors, such as overeating. Increasing attentional control will thus help to improve eating behaviors. Attention is an important aspect of Mindfulness Based Interventions (MBIs). While it is shown that these interventions are able to improve eating behaviors, the underlying mechanism is unknown. Improved attentional control towards food cues might play a role.
Aim: To investigate whether food-related attentional control is improved by a Mindful Eating intervention and whether activation changes occur in attentional control-related brain areas, thereby exploring whether this might underlie the beneficial effects of MBIs on eating behaviors.
Method: 44 healthy subjects who were motivated to change their eating habits, participated in an 8-week Mindful Eating intervention or Educational Cooking intervention (active control). Attentional control was measured with a food Stroop task in an MRI scanner. For this task, changes in reaction times and BOLD responses from pre- to post-intervention were analyzed.
Results: No differences in reaction times and BOLD responses were found between the intervention groups from pre- to post-intervention, but there were differences when looking over both time points and intervention groups. There was a significant main effect of food interference words (versus positive emotional words) on reaction times. For food interference versus neutral words, the left inferior and superior frontal gyrus and the left middle temporal gyrus showed specific activation. The left inferior frontal gyrus, the left inferior parietal lobule, and the left angular gyrus showed greater activation for food words versus positive emotional words.
Conclusion: There was no difference in changes in attentional control between the Mindful Eating intervention and the active control intervention. This implies that changes in attentional control might not underlie the positive effects of MBIs on eating behavior.

Keywords: mindful eating, attentional control, food cues, eating behavior, food Stroop, fMRI

Introduction

In our current obesogenic environment, we are constantly confronted with food cues (Lake & Townshend, 2006), such as advertisements for food products and the sight and smell of food items themselves. Because food cues increase the motivation to eat, sensitivity to food cues can lead to increased food intake and overeating (Berthoud, 2004; Colagiuri & Lovibond, 2015). When overeating occurs frequently, this can lead to obesity, a problem that has reached epidemic proportions during the last decades (Abarca-Gómez et al., 2017) and is associated with severe health risks and increased health care costs (Hruby & Hu, 2015). It has been found that an attentional bias towards food cues (Boswell & Kober, 2016; Seage & Lee, 2017; Werthmann, Jansen, & Roefs, 2015) and attentional control over this bias (Bazzaz, Fadardi, & Parkinson, 2017; Kakoschke, Kemps, & Tiggemann, 2014) are related to eating behavior. A lack of control results in a larger effect of food cues on food intake and can lead to overeating and obesity. Increasing attentional control in relation to food cues might therefore help to tackle issues with overeating and excess body weight (Bazzaz et al., 2017; Forcano, Mata, de la Torre, & Verdejo-Garcia, 2018).

Attention is an important element of Mindfulness Based Interventions (MBIs) (Kabat-Zinn, 2003). These interventions that have mindfulness as their main element, specifically focus on paying attention to the present moment, on purpose and non-judgmentally (Kabat-Zinn, 1994). One essential part is mindful meditation, which involves sustaining mindful attention for a longer period of time. MBIs are beneficial for several aspects of mental and physical health in both clinical and nonclinical populations (Goldberg et al., 2018; Khoury, Sharma, Rush, & Fournier, 2015). Among these benefits is their ability to increase healthy eating behaviors (e.g. decrease overeating) (Carrière, Khoury, Günak, & Knäuper, 2018; Rogers, Ferrari, Mosely, Lang, & Brennan, 2017), where these interventions also seem to specifically benefit eating behaviors related to external cues (O'Reilly, Cook, Spruijt-Metz, & Black, 2014; Warren, Smith, & Ashwell, 2017). However, it is unclear which underlying mechanisms drive these improvements (Rogers et al., 2017). By improving the ability to focus and sustain attention through mindful meditation and other mindfulness-based practices, attentional control might increase. Several studies indeed found that MBIs and mindful meditation may be able to increase attentional control (Becerra, Dandrade, & Harms, 2017; Chiesa, Calati, & Serretti, 2011; Moore, Gruber, Derose, & Malinowski, 2012; Moore & Malinowski, 2009), but note that not all studies found this effect (Josefsson, Lindwall, & Broberg, 2014; Lao, Kissane, & Meadows, 2016; Lykins, Baer, & Gottlob, 2012). Thus, there are indications that MBIs are able to improve attentional control, although the literature is not unequivocal (Chiesa et al., 2011;

Lao et al., 2016; Vago, Gupta, & Lazar, 2019). It might be that these improvements in attentional control are the underlying mechanism for the increases in healthy eating behaviors exerted by MBIs.

The aim of this study was therefore to investigate whether an MBI can increase attentional control in relation to food cues. This will help to give insight in whether attentional control is a possible mechanism of action of MBIs. Because we were interested in the effects on healthy eating behaviors, we used an MBI that also focused specifically on food-related attention, namely a Mindful Eating intervention (Janssen et al., 2018). It is important to isolate the mindfulness-related intervention-specific factors and distinguish these from non-specific factors of the intervention (e.g. the group, weekly session) (Vago et al., 2019). We therefore incorporated an Educational Cooking intervention as an active control condition, which is matched with the Mindful Eating intervention for group contact, effort, and time. This way, we were able to rule out beneficial effects of intervention aspects other than the mindfulness-based elements.

We used a food Stroop task (Janssen, Duif, van Loon, et al., 2017; Nijs, Franken, & Muris, 2010) to measure attentional control associated with food cues. This was a modified version of the original Stroop task (Stroop, 1935), in which subjects were asked to name the color of food, positive emotional and neutral words as fast as possible and to ignore the words themselves. If attention was nonetheless drawn to the food words, reaction times for color-naming would increase. Control over attention towards food cues was thus reflected in the reaction times for the food words in the food Stroop task. The emotional words were used to be able to distinguish general improvements in attentional control from specific attentional control related to food cues. Hence, with this task, we could specifically measure attentional control in relation to food cues.

Furthermore, we were interested in whether activations in attentional control-related brain areas would be changed after the Mindful Eating intervention. It is known that training mindfulness can change patterns of neural activation (Falcone & Jerram, 2018) and also specifically neural activation in areas related to attentional control (Malinowski, 2013). However, as mentioned by Warren and colleagues (2017), more fMRI studies are needed that specifically look into brain activity changes in relation to external food cues. In this study, we used fMRI to study changes in brain activation from pre- to post-intervention during the food Stroop task, a task that demands attentional control to ignore the external food cues. This would help to elucidate which areas respond differently after the Mindful Eating intervention.

As we were interested in improvements in attentional control by a food-focused MBI, we also specifically looked at activation changes in brain regions that are known to be related to attentional control and mindfulness. For this, we chose to use the lPFC, the ACC and the insula together as a ROI, as these brain regions are involved in attentional control (Asplund, Todd, Snyder, & Marois, 2010; Crottaz-Herbette, Menon, & Crottaz-Herbette, 2006; Hartikainen & Knight, 2003; Macleod & Macdonald, 2000; Nelson et al., 2010) and also appear to be altered by mindfulness interventions (Fox et al., 2014; Gotink, Meijboom, Vernooij, Smits, & Hunink, 2016; Young et al., 2018). If attentional control would indeed be an underlying mechanism of the increase in healthy eating behaviors after MBIs, activation changes during the food Stroop task could be expected in these areas.

Additional to these measures of attentional control, we also wanted to check whether the Mindful Eating intervention led to consistent changes in daily eating behaviors in terms of less overeating and healthier eating. Because the intervention may change awareness of eating behaviors and thus influence subjective measures of eating behaviors, we wanted to use an objective measure of consistent changes in food intake, as a general reflection of changes in healthy eating behaviors. We therefore chose changes in BMI from pre- to post-intervention as an indirect, but objective, measure. If the Mindful Eating intervention brings about stable increases in healthy eating behaviors that led to weight loss, this would be reflected in a decreased BMI. We were then interested in whether changes in food-related attentional control were accompanied by changes in BMI, which would support that the improvements in attentional control are underlying the effects of the intervention on healthy eating behaviors.

Thus, we used behavioral measures and fMRI in this study to investigate whether a Mindful Eating intervention increases attentional control with regards to external food cues. Changes in BMI were included to assess consistent changes in food intake as a reflection of healthy eating behaviors. We hypothesized that the Mindful Eating intervention would improve attentional control in relation to external food cues and that this improvement is accompanied by an increase in healthy eating behaviors. This would then implicate that improvements of attentional control are a possible mechanism that underlie the beneficial effects of MBIs on healthy eating behaviors. As improved attentional control would be reflected by decreased reaction times and increased activation in brain areas related to attentional control, we expected to see shorter reaction times and enhanced brain activation in the lPFC, ACC, and insula after the Mindful Eating intervention compared to pre-intervention and compared to the active control. Additionally, we expected to see decreases in BMI after the Mindful Eating intervention as a reflection of increased healthy eating behaviors.

Methods

Design

A randomized, actively controlled trial was used to compare the effects of Mindful Eating on food-related attentional control compared to Educational Cooking as an active control condition. Measurements were taken before and after the interventions. The current study was part of a larger study, of which the results are reported elsewhere (Janssen, 2017; Janssen, Duif, Speckens, et al., 2017; Janssen et al., 2018; Janssen, Duif, van Loon, et al., 2017). Note that baseline (pre-intervention) analyses for the current study are already published (Janssen, Duif, van Loon, et al., 2017).

Subjects

Subjects were recruited through advertisement in Nijmegen and surroundings. Subjects were included if they had a strong motivation to change unwanted eating habits, were aged 18-55, were right-handed, and had a BMI between 19 and 35. Subjects were excluded if they previously took part in a Mindfulness-Based Stress Reduction or Mindfulness-Based Cognitive Therapy course. Further exclusion criteria were eating disorders (including binge eating disorder), extremely high restrained eating scores (Dutch Eating Behavior Questionnaire, males≥4.0, females≥3.6; (van Strien, Frijters, Bergers, & Defares, 1986), current dieting (following a strict diet to lose weight and/or being in treatment with a dietitian), changes in body weight of more than 5 kg during the last two months, depression/anxiety state scores > 11 on the Hospital Anxiety and Depression Scale (HADS) (Zigmond & Snaith, 1983), (a history of) other clinically relevant psychiatric or neurological disorders, current psychological treatment, current use of psychopharmaceuticals, (a history of) taste or smell impairments, diabetes mellitus, (a history of) hepatic, cardiac, respiratory, renal, cerebrovascular, endocrine, metabolic or pulmonary diseases, uncontrolled hypertension (diastolic pressure > 90 mmHg, systolic pressure > 160 mmHg), food allergies relevant for the study (in relation to the eating exercises in the intervention programs), deafness, blindness and sensorimotor handicaps, drug or alcohol addiction, insufficient mastery of the Dutch language, and contra-indications for MRI. All subjects gave written informed consent and received financial compensation for the lab visits. Additionally, the intervention program was free of charge. The protocol for the study was approved by the local ethics committee (CMO region Arnhem-Nijmegen, the Netherlands, 2013-188).

In total, 92 healthy right-handed subjects were included. Following behavioral testing and scanning, 33 subjects were not included in the analysis due to having withdrawn from participation (N=20), having artifacts or incidental findings in their MRI data (N=8), having failed to meet the inclusion criteria during the post-intervention measurements (N=4: pregnant (N=2), loss of smell (N=1), and severe infection (N=1)) or being an outlier on the behavioral test (N=1, see Behavioral analysis). Because we aimed to uncover working mechanisms of the Mindful Eating intervention, we included only those subjects that received a probably sufficient dose of training to be effective. Therefore, only subjects who did at least 5 sessions of the assigned intervention were included. This per protocol group consisted of 44 subjects (**Table 1**).

Procedure

Inclusion and exclusion criteria, as well as matching criteria, were checked for all subjects during an intake session that preceded the test sessions. Matching criteria included gender, age, BMI, and at-home experience with meditation and yoga. During the intake session, subjects rated the Stroop words (arousal and valence) and completed the Dutch version of the National Adult Reading Test (DART) to evaluate educational level and verbal IQ (Schmand, Bakker, Saan, & Louman, 1991). Included subjects were invited for measurement sessions at the laboratory before and after the intervention. These sessions started at 11.00 AM or 12.30 PM and had a duration of approximately 3.5 hours. The pre- and post-intervention test sessions took place within a month before and after the start of the intervention, respectively. All subjects were instructed to eat and drink nothing (except water) during the 4 hours before the test sessions. Prior to the sessions, use of recreational drugs during a period of one week and alcohol consumption during a period of 24 hours were not allowed. This was all checked at the beginning of the sessions with a self-report compliance questionnaire. Before the start of the Stroop task, measurements of subjects' height, weight, and waist and hip circumference were taken. The Stroop task was performed in the MRI scanner and started approximately 1 hour after the start of the test sessions.

Additional measurements were taken during the measurement sessions for other goals related to the larger study (Janssen, 2017; Janssen, Duif, Speckens, et al., 2017; Janssen et al., 2018; Janssen, Duif, van Loon, et al., 2017). Prior to the Stroop task, these additional measurements included questionnaires and the digit span test (Groth-Marnat, 2009), which were performed outside the MRI scanner, and hunger ratings, which were performed inside the scanner.

Stroop task

Before going into the scanner, subjects received written instructions on the Stroop task. In the scanner, subjects first got familiar with the button-color combinations and completed 10 practice trials with feedback on correctness. For the practice trials, colored strings of 6 symbols were presented instead of words. Four button-color combinations were counterbalanced across subjects, but the combination stayed the same within a subject. The food Stroop task consisted of 160 trials and had a duration of approximately 7 minutes, with a 30-seconds break halfway. Subjects were instructed to identify the color of the word that was shown on the screen by pressing one of four buttons on the button box in their right hand. They were asked to do this as accurately and quickly as they were able to. Words on the screen were displayed in either blue, red, yellow, or green and each of the buttons corresponded with one of these colors. The words presented were either interference words or matched neutral words. Interference words consisted of 20 food words and 20 positively valenced emotional words. Each of the neutral words was either matched to a food word (20) or an emotional word (20) in terms of length, syllable number and usage frequency as reported in the SUBTLEX-NL database (Keuleers, Brysbaert, & New, 2010). Thus, in total there were 4 word types (food, emotional (emo), neutral matched to food (fneu), and neutral matched to emotional (eneu)). All words were presented twice during the task in a different color, which adds to the total of 160 trials. Word types were presented intermixed, with the order of the words pseudorandomized and counterbalanced across subjects and sessions. The colored words were presented for 1.5 seconds after a fixation period of 2-4 seconds (jittered, drawn from a Poisson distribution, mean=2.6 s) (**Figure 1**). During the task, subjects received no feedback. Subjects viewed all stimuli via a mirror attached to the head coil.

The food words used in the task consisted of 20 generally appetizing and high calorie food words and were a selection of words from lists reported in previous studies (Nijs et al., 2010; Phelan et al., 2011). The 20 positive emotional words and the 40 neutral words were drawn from the Dutch Words Database (Moors et al., 2013). Positive emotional words were selected on reported positive valence and arousal ratings of 5 or above. Neutral words were selected on positive valence and arousal ratings between 3 and 5.

During the intake session, subjects were asked to rate the arousal and valence of the words with visual analogue scales, to validate differences between the neutral and the interference words.

Randomization

Subjects either followed a Mindful Eating or an Educational Cooking intervention, to which they were randomly assigned through minimization (Scott, McPherson, Ramsay, & Campbell, 2002) regarding gender (male/female), age (18-25; 26-35; 36-45; 46-55), experience with yoga or meditation (never; 0 – 2 years; 2 – 5 years; 5 – 10 years; > 10 years), and BMI (19 – 24.9 normal weight; 25 – 29.9 overweight; 30 – 35 moderately obese).

Assignment to the groups was done using a computer algorithm that took into account these minimization factors for balancing. The algorithm was developed by an independent statistician from Radboud University Medical Center. Of the 92 included subjects, 45 subjects were assigned to Mindful Eating and 47 to Educational Cooking (active control group). The per protocol group consisted of 44 subjects, with 24 in the Mindful Eating group and 20 in the active control group (**Table 1**). As no more than 10-15 subjects could take part in the training at a time, there were 3 consecutive training blocks for each of the interventions (3 for Mindful Eating and 3 Educational Cooking). To guarantee baseline measurements uninfluenced by intervention expectations, subjects were announced about their assigned intervention only after the pre-training test session.

Interventions

General. Both intervention trainings comprised 8 weekly group sessions of 2.5 hours, which took place from 7 PM-9.30 PM. Additionally, an extra day (6 hours) fully devoted to the goals of the intervention took place towards the end of the intervention. Subjects were also asked to spend 45 minutes per day on homework assignments and to keep track of the amount of time that they actually invested in the homework by writing this down on homework sheets. The interventions matched each other for group contact, effort, and time, but differed substantially with regard to content. To avoid a selection bias of subjects with an interest for mindfulness, the programs were named "eating with attention" (Mindful Eating) and "eating with knowledge" (Educational Cooking).

Mindful Eating. The goal of the Mindful Eating intervention was to promote awareness of the thoughts and sensations around food and eating. The intervention was based on the Mindfulness-Based Stress Reduction program (Kabat-Zinn, 1990) in terms of formal mindfulness practices, such as the body scan and sitting meditation, that are intended to increase general mindfulness skills. Additionally, informal mindfulness practices with focus on Mindful

Eating were incorporated in the intervention, which were extracted from the Mindful Eating, Conscious Living (MECL) program (Bays, 2009).

The weekly session each had a theme: the automatic pilot, observing hunger and other internal states, boundaries in eating behavior, stress-related eating, coping with stress, coping with (negative) thoughts, self-compassion and self-care, and integrating mindfulness in daily life. The homework involved guided formal mindfulness exercises (using CDs) and informal mindfulness exercises focused on one moment a day (e.g. mealtime). The extra day consisted of a silent day, during which the group of subjects consumed a meal in silence and did formal mindfulness exercises. The Mindful Eating trainings were developed and given by qualified psychologist and psychiatrist that had graduated from the post-graduate mindfulness teacher training at the Radboud University Medical Center for Mindfulness, which was also the location of the sessions.

Educational Cooking. The goal of the Educational Cooking intervention was to promote knowledge of food and eating. Subjects participated in group sessions with cooking workshops that focused on healthy diet choices and healthy preparation of foods, based on the guidelines of the Netherlands Nutrition Centre (www.voedingscentrum.nl). The themes of the sessions were healthy eating and nutrition, benefits and preparation of fruits and vegetables, different kinds of fats, salt and ways to avoid salt usage, reading information on food packages, healthy snacking, healthy choices while eating at restaurants, and integrating healthy cooking and eating in daily life. The homework involved counting the caloric value of one meal a day (noted in the homework diary) and practicing cooking techniques or conscious grocery shopping (e.g. reading labels). The extra day consisted of a balance day, during which the subjects followed all the learned healthy diet guidelines for each meal and snack. A qualified dietician from Wageningen University had put together the Educational Cooking training sessions and also gave the trainings. A professional chef guided the cooking workshops during the sessions. The sessions took place in a special kitchen complex belonging to the faculty of the Nutrition and Dietetics of the Hogeschool of Arnhem-Nijmegen.

MRI data acquisition

Whole-brain functional images, using blood oxygen level dependent (BOLD) contrast, were obtained with a Siemens 3T Skyra MRI scanner (Siemens Medical system, Erlangen, Germany) and a 32-channel coil. Per functional volume, 34 axial slices were obtained in ascending direction using a multi-echo echo-planar imaging (EPI) sequence. This method of parallel acquisition for functional images reduces image distortion (Poser, Versluis, Hoogduin, & Norris, 2006). The following scan parameters were used for the functional imaging: a voxel size of 3.5x3.5x3 mm, a repetition time (TR) of 2070 ms, echo times (TEs) of 9 ms, 19.25 ms, 29.5 ms, and 39.75 ms, a flip angle of 90°, and a field of view (FOV) of 224 mm. Prior to the acquisition of the functional images, a T1-weighted MP-RAGE anatomical scan was obtained, consisting of 192 sagittal slices. The following scan parameters were used for the anatomical scan: a voxel size of 1x1x1 mm, a TR of 2300 ms, a TE of 3.03 ms, a flip angle of 8°, and a FOV of 256 mm.

Analysis

Behavioral analysis. For the reaction times of the Stroop task, The Grubb's test (Barnett & Lewis, 1974) was used to detect outliers for each condition (food, emo, fneu, eneu) and for each time (pre, post) separately. Here, outliers were defined as >3 SD difference from the mean (N=1). For the accuracies of the Stroop task, subjects with an accuracy rate of ≤ 50% were deemed as outlier (N=0).

A repeated measures ANOVA (SPSS 25, Chicago, IL) was constructed with Intervention (Mindful Eating, Educational Cooking) as between-subject factor and Time (pre-intervention, post-intervention) and Word Type (food, emotional) as within-subject factors. The dependent variable was the mean reaction time for correct responses for the salient words (food, emo) corrected by subtraction of the mean reaction time for correct responses for their matched neutral words (fneu, eneu). This repeated measures ANOVA allowed us to test our hypothesis whether Mindful Eating (as compared to Educational Cooking) does improve attentional control over food-related words (as compared to positive emotional words).

It was tested whether the interventions led to changes in BMI by constructing a repeated measures ANOVA with Time as within-subject factor, Intervention as between-subject factor and BMI as dependent variable.

Our hypothesis that changes in BMI would be accompanied by changes in attentional control was tested by adding the difference between post-intervention and pre-intervention BMI as a covariate of interest to a repeated measures ANOVA. The dependent variable was the mean reaction times for the salient words (food, emo) corrected with their matched neutral words (fneu, eneu). Within-subject factors were Time and Word Type.

For all behavioral analyses, effects were deemed statistically significant when they met the threshold of $p<0.05$.

MRI data preprocessing. All images were preprocessed with SPM8 (www.fil.ion.ucl.ac.uk/spm). To correct for motion, volumes for each echo time were realigned. Here, the first echo was used to estimate the realignment parameters, which were then used to realign the other echoes. As a result of the EPI sequence used, the four echo images needed to be combined into one MR volume. For this, an optimized echo weighting method was applied (Poser et al., 2006) that used 31 volumes obtained before the start of the actual experiment. The combined functional images were then slice-time corrected using temporal interpolation, with the acquisition time of the middle slice as reference. Next, the functional and structural data were co-registered to the standardized functional or structural space of the Montreal Neurological Institute (MNI) brain template. The structural images were segmented with a unified segmentation approach, which also produced a transformation matrix. This was followed by spatial coregistration of the structural images to the mean of the functional images. After this, the transformation matrix was used to normalize the final functional and anatomical images into MNI space (resampled at voxel size 2x2x2). Lastly, the normalized functional imaged were spatially smoothed with an isotropic 8mm full-width at half-maximum Gaussian kernel.

fMRI analysis. The fMRI data were statistically analyzed with SPM 12 (www.fil.ion.ucl.ac.uk/spm), using a general linear model (GLM) approach. At the first level, a random effects model was used to analyze subject-specific data in an event-related design which included both the pre-interventional and post-interventional test sessions. For both sessions, the regressors of interest were specified, which represented the onset of food, emotional (emo), neutral matched to food (fneu), and neutral matched to emotional (eneu) words. Two separate regressors represented the incorrect responses and the misses (no button press before the next word appeared), if they were present. All onsets were modeled using a stick function and were convolved with the canonical hemodynamic response function (HRF) to reflect the BOLD signal. Additionally, the time and dispersion derivatives of the HRF and the out-of-brain signal variation were included in the model. The six movement parameters produced by the realignment preprocessing step, as well as their time derivatives, were included to represent head movement. An autoregressive AR(1) model was used to correct for serial correlations. To remove low frequency drifts, high pass filtering (128s) was applied to the time-series of the functional images.

For the second level analyses, contrast images were calculated at the first level for food minus neutral (food-fneu) and for food minus neutral versus emotional minus neutral ([food-fneu]-[emo-eneu]). These contrast images were acquired for pre-intervention and post-intervention together (pre+post) and for post-intervention versus pre-intervention (post-pre), by adding Session as a factor and looking across the sessions and at the difference between sessions, respectively.

First, as a validity check of the food Stroop task, the pre+post contrast images were used in a two-sample t-test, with a contrast across both intervention groups. For this test of a main effect across time points and interventions, the food-fneu contrast was used to check whether the food Stroop task shows brain activation related to food-related attentional control and the [food-fneu]-[emo-eneu] contrast was used to check whether there are brain regions that show different brain activations for food-related compared to emotion-related attentional control.

Second, the post-pre contrast images were used in a two-sample t-test, with intervention as between-subject factor. In addition, the difference between post-intervention and pre-intervention BMI (Z-score) was taken into account as a covariate of interest, to explore whether changes in BMI were related to food-related attentional control brain activation changes. To investigate our hypotheses about the effect of the Mindful Eating intervention on the brain activations, the post-pre contrasts were used for both the food-fneu and the [food-fneu]-[emo-eneu] contrasts. Here, the food-fneu contrast was used to test whether brain activation for attentional control over food words changed over time. The [food-fneu]-[emo-eneu] contrast was then used to test whether brain activation for food-related attentional control changed differently from brain activation for emotional words. These two contrasts were both investigated with intervention as between-subjects factor, to test whether these effects on brain activity were larger for the Mindful Eating intervention compared to the control intervention. Thus, these contrasts together could be used to test all our hypotheses about changes in brain activation.

Analyses were performed for the whole-brain and for a predefined anatomical ROI. For the ROI analysis, the lPFC, the ACC, and the insula (see introduction for justification) from the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) were used as a small search volume. Effects were deemed statistically significant when they met the required threshold of $p<0.05$, family wise error corrected (FWE) for multiple comparisons at the voxel level, for whole-brain and the ROI search volume.

Results

Behavioral results

There was a significant effect of Word Type on reaction times, where food words showed increased interference (i.e. longer reaction times) compared to emotional words (Main effect of Word Type (food-corrected, emotional-corrected): $F(1,42)=7.004$, $p=0.011$; food-corrected: M=26 ms, SEM=9 ms, emotional-corrected: M=-8 ms, SEM=9 ms).

There was no significant interaction between Intervention (Mindful Eating, Educational Cooking), Word Type (food, emo), and Time (pre, post) ($F(1,42)=0.017$, $p=0.897$). In addition, there was also no main effect of Time ($F(1,42)=0.001$, $p=0.971$), nor an interaction between Time and Word Type ($F(1,42)=0.097$, $p=0.757$), nor an interaction between Intervention and Time ($F(1,42)=0.000$, $p=0.995$). Together, this suggests that there was no significant change in attentional control over time: not intervention-specific, nor across interventions.

The groups differed at trend level in BMI change over time (interaction Time x Intervention for BMI, $F(1,42)=3.535$, $p=0.067$; Mindful Eating pre: M=26.7, SEM=0.9, Mindful Eating post: M=26.8, SEM=0.9, Educational Cooking pre: M=25.5, SEM=0.7, Educational Cooking post: M=25.0, SEM=0.6). Exploring this trend further revealed that BMI did decrease significantly over time for the Educational Cooking intervention ($F(1,19)=5.110$, $p=0.036$), but not for the Mindful Eating intervention ($F(1,23)=0.003$ $p=0.956$). There were no further significant interactions with BMI.

Neuroimaging results

Brain regions that responded to attentional control for the salient food words (food) compared to matched neutral words (fneu) were investigated by using the food-fneu contrast over both intervention groups for both time points together. This contrast gave significant BOLD responses at the whole-brain corrected threshold (FWE<.05, peak-level) for the left inferior and superior frontal gyrus and the left middle temporal gyrus (**Table 2**; **Figure 2A**). Brain regions that responded more to food words compared to emotional words were investigated by using the [food-fneu]-[emo-eneu] contrast over both intervention groups and both time points together. For this contrast, BOLD responses in the left inferior frontal gyrus, the left inferior parietal lobule, and the left angular gyrus were significant (**Table 2**; **Figure 2B**). ROI analyses did not reveal any additional regions (**Table 2**).

For both the food-fneu and [food-fneu]-[emo-eneu] contrasts, there was no significant difference in BOLD-response for the Mindful Eating group compared to the Educational Cooking group over time (i.e. interaction of Intervention x Time x Word Type). In addition, there was no main effect of Time, nor an interaction between Time and Word Type or an interaction between Intervention and Time (all pFWE<.05). Together, this suggests that there was no significant change at the neural level in food-related attentional control over time: not intervention-specific, nor across interventions.

There was also no significant response related to changes in BMI.

Discussion

In this randomized and active-controlled experimental study, the aim was to explore whether an MBI increased attentional control in relation to food cues. To this end, a food Stroop task was used before and after a Mindful Eating intervention, with an Educational Cooking intervention as an active control. Notably, this Stroop task allowed to assess food-specific (compared to emotion-specific) attentional control and also controlled for non-specific word effects. Reaction times, as well as neural BOLD responses, were used to assess changes in attentional control. Behavioral findings indicated that the food Stroop task was able to measure attentional bias towards food words, reflected in longer reaction times for food words compared to neutral and positively valenced words, but that a Mindful Eating intervention did not significantly improve attentional control over this bias. This is also reflected by our findings on the neural level: the left inferior and superior frontal gyrus and the left middle temporal gyrus showed greater BOLD responses for food words than matched neutral words and the left inferior frontal gyrus, the left inferior parietal lobule, and the left angular gyrus showed greater BOLD responses for food word compared to positive emotional words. These brain regions thus showed specific neural activation when food-related attentional control is exerted during the food Stroop task, indicating that there was a difference in neural attentional processes for food-related words compared to neutral and positive emotional words. This supports the behavioral findings that the task was able to measure food-related attentional bias specifically. There was no significant difference in BOLD responses after the Mindful Eating intervention compared to the Educational Cooking intervention, again indicating that the Mindful Eating intervention did not significantly improve attentional control. Thus, this well-designed study was able to detect food-specific attentional control at the behavioral and neural level, but did not find greater changes on either the behavioral or neural level following the Mindful Eating intervention compared to the active control intervention.

These findings are inconsistent with our hypothesis that food-related attentional control would improve after the Mindful Eating intervention and that this could thus underlie the enhancing effects of MBIs on healthy eating behaviors.

A previous study with an overlapping sample that was based on only the pre-intervention measurements (Janssen, Duif, van Loon, et al., 2017) did find a general interference effect of food words relative to neutral and emotional words. Our current results showed this same main effect of food-words compared to neutral and positive emotional words.

This main effect is consistent with existing literature. The finding of a specific BOLD response for food-words in the left inferior frontal gyrus is in line with studies that found an effect of incongruent versus congruent color words in the regular color-naming Stroop task in this brain region (Banich et al., 2000; Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000; Liu, Banich, Jacobson, & Tanabe, 2004; Milham et al., 2001). Furthermore, a study showed that the left inferior frontal gyrus is involved in food-cue reactivity in relation to self-control (Lopez, Hofmann, Wagner, Kelley, & Heatherton, 2014). This study used the go/no-go task that measured response inhibition and not attentional control specifically, but it is likely that competition between responses is also involved in the interference effect of the Stroop task (Dyer, 1973; Stroop, 1935). Thus, the current results seem consistent with this previous work that showed involvement of the left inferior frontal gyrus in food-specific self-control. Furthermore, the food-specific attentional bias on the behavioral level that was found in this study is consistent with previous findings that both obese and normal-weight subjects had longer reaction times for food words than for neutral words in a Stroop task (Nijs et al., 2010).

Although the food Stroop task was able to measure food-specific attentional control, we did not find a significant increase in food-related attentional control after the Mindful Eating intervention. This is inconsistent with the variety of studies that found that MBIs have the ability to improve attentional control (Becerra et al., 2017; Chiesa et al., 2011; Moore et al., 2012; Moore & Malinowski, 2009). However, our results are consistent with several studies that did not find this effect (Josefsson et al., 2014; Lao et al., 2016; Lykins et al., 2012). Taken together, it is relevant to evaluate other possibilities for mechanisms that could drive the effect of MBIs on eating behavior. These possibilities include increased awareness of internal cues, decreased emotional eating, and increased acceptance.

First of all, it is possible that an MBI can facilitate an increase in awareness of internal hunger and satiety cues (Beshara, Hutchinson, & Wilson, 2013; Hölzel et al., 2011). Important elements of MBIs are focusing on the breath and doing a body scan, which entails scanning your body parts with your attention. These exercises may increase general awareness of one’s body and sensations in the body, including sensations such as hunger, fullness and satiety. In turn, this may decrease eating when not hungry and overeating once satiated. This is thus a possible mechanism underlying the increases in healthy eating behaviors after MBIs (Carrière et al., 2018; Rogers et al., 2017).

Another possibility is MBI-induced decreased emotional eating. There is evidence that emotional eating is linked to unhealthy eating behaviors (Konttinen, Männistö, Sarlio-Lähteenkorva, Silventoinen, & Haukkala, 2010) and that MBIs may reduce emotional eating (Mantzios & Wilson, 2015), possibly because mindfulness exercises can reduce reactivity to emotions and can reduce stress. It is thus possible that a reduction in emotional eating by MBIs underlies the improvements in healthy eating behaviors.

Apart from increasing bodily awareness and reducing stress and reactivity to emotions, MBIs focus on acceptance and absence of judgement (Kabat-Zinn, 1990). Other studies showed that MBIs focused on acceptance have the ability to enhance healthy eating behaviors (Alberts, Mulkens, Smeets, & Thewissen, 2010; Tapper et al., 2009). It is thus possible that increased acceptance is driving the beneficial effects of MBIs on healthy eating behaviors.

Thus, alternative mechanism that could drive the increases in healthy eating behaviors after MBIs include: increased awareness of internal cues, decreased emotional eating, and increased acceptance.

Limitations of the study should also be considered. Although the study was generally well-designed, there could be some limitations that are related to the task, using changes in BMI as a reflection of changes in healthy eating behaviors, and the effectiveness of the interventions.

Although the Stroop task is widely used to study attention, the task was possibly not optimal to measure the specific food-related attentional control that we aimed to measure. A study found that although a fast automatic processing bias toward salient words is of importance in an emotional Stroop, it is not necessarily reflected in reaction times (Franken, Gootjes, & van Strien, 2009). As the food Stroop we used is similar to the emotional Stroop task, it could thus be that the reaction times do not reflect the level of attentional bias and attentional control. Therefore, it could be that attentional control over a food-related attentional bias improved, but that we were simply not able to detect it with the reaction times for the food Stroop task.

Another limitation of the food Stroop task could be its ecological validity. The task used food words as interference stimuli. However, most food cues encountered are not in the form of individual words, but as pictures and videos of the food items, spoken words, or food items themselves. This difference in representation of the food cues could have led to not finding changes in food-related attention control for the task, while the intervention may have had an effect in everyday life situations involving food cues. As the BOLD responses were also measured during the food Stroop task, this limitation could have influenced these outcomes as well. However, the previous study that looked at the baseline measurements of the same food Stroop task (Janssen, Duif, van Loon, et al., 2017) found an association between obesity and neural activations, while no association was found with the reaction times. This would imply that the neural data is more sensitive than the reaction times and would thus be able to show changes if they would be present. Still, the low ecological validity could have inhibited us from finding a significant effect on both the reaction times and the neural data. Thus, the food Stroop task used in this study could have been not optimally suitable to reflect the changes in food-related attentional control that may have happened after having followed an MBI.

The Educational Cooking group showed a decrease in BMI after the intervention. This decrease is likely caused by the emphasis of the intervention on adhering to the Dutch nutritional guidelines for a healthy diet and not by improvements in attentional control, as the measures of attentional control did not significantly change. In contrast, no significant changes in BMI were found over time for the Mindful Eating group, indicating that this intervention was not effective in reducing weight. However, this does not necessarily mean that there was no improvement in healthy eating behaviors. Studies found that unwanted eating behaviors, such as binge eating and emotional eating, do decrease after MBIs, but that the effectiveness for weight loss is not so clear (Katterman, Kleinman, Hood, Nackers, & Corsica, 2014). Thus, our Mindful Eating intervention could still have increased healthy eating behaviors among the subjects without an effect on weight. Additionally, the intervention could still have improved everyday life food-related attentional control, but without significant changes in calorie consumption and thus in BMI. Thus, the lack of change in BMI after the Mindful Eating intervention does not necessarily imply that healthy eating behaviors and food-related attentional control were not improved.

Another limitation could be that the Mindful Eating intervention was not effective enough as compared to other MBIs used in studies that did find an effect on attentional control (Becerra et al., 2017; Chiesa et al., 2011; Moore et al., 2012; Moore & Malinowski, 2009) and that did find effects on weight loss (Carrière et al., 2018; Rogers et al., 2017). The Mindful Eating intervention was based on the Mindfulness-Based Stress Reduction (MBSR) program (Kabat-Zinn, 1990), from which no formal exercises were omitted. No changes were made in terms of duration and effort either. Therefore, it is unlikely that the Mindful Eating intervention differed significantly in terms of effectiveness from other researched MBIs. However, it could be that the motivation and expectations of the subjects caused differences in effectiveness. Subjects were included to participate in our study if they were motivated to change unwanted eating habits. As this is broadly defined, the group could be very heterogeneous with regard to their motivation to put time and effort in the exercises and to their expectations of the intervention. To prevent results from being influenced by subjects that were not committed at all to the interventions, only subjects that came to five out of nine training sessions (8 weekly sessions and the extra day) were included for the analyses and results. However, this only took into account attendance at the sessions and not the engagement during the sessions or the commitment to the homework. It is shown that time investment in formal exercises at home are related to effects of the MBI (Carmody & Baer, 2008). Therefore, it cannot be ruled out that the group of subjects were not motivated enough to actually commit to the interventions, possibly having led to a lack of effectiveness of the intervention and thus even a lack of significant changes in attentional control.

In short, there were some limitations of our study regarding the food Stroop task, the use of BMI as a reflection of healthy eating behaviors, and the effectiveness of the intervention. These limitations could have gotten in the way of finding changes in attentional control, while attentional control may actually underlie the positive effects of MBIs on healthy eating behaviors. Therefore, it may be that the results of the current study were not actual null results, but caused by type II errors. However, other studies also did not find an effect of MBIs on attentional control (Josefsson et al., 2014; Lao et al., 2016; Lykins et al., 2012) or an effect on weight loss (Carrière et al., 2018; Rogers et al., 2017), supporting that the negative findings of the current study were valid.

Furthermore, the evident strengths of our study design speak in favor of considering our negative findings as true null findings. The randomization of the groups prevented baseline differences between the intervention groups, while the active control intervention enabled us to specifically measure the effect of mindfulness-specific aspects of the intervention. This together greatly reduced the interference of confounding factors. Other studies that found an effect of MBIs on attentional control often did not have an active control condition (Becerra et al., 2017; Chiesa et al., 2011; Moore et al., 2012). Therefore, aspects of the MBI other than mindfulness practices, could have led to finding a difference between the MBI and the non-active control condition. This would explain why we could not find a difference between the Mindful Eating intervention and active control intervention. Another strength of our study that makes it unlikely that the intervention in itself was not effective, were the well-trained mindfulness trainers that guided the Mindful Eating intervention. These strengths thus minimized the likelihood of an effect of confounding factors and ineffective treatment on our findings, suggesting that even though there were some limitations, it is likely that our findings were true null findings.

Considering the above strengths and limitations, future research is needed to elucidate whether enhancements in attentional control indeed do not play a central role in the effect of MBIs on healthy eating behaviors and whether other mechanisms are involved.

These studies should additionally use other measurements of attentional control such as eye-tracking. This particularly allows to detect the early attention towards and the later disengagement from stimuli (Duchowski, 2002). This disengagement, or switching, of attention from food cues towards other cues would represent the attentional control. The use of eye-tracking may thus also help to disentangle early from later attentional processes. If a paradigm will be used with pictures of foods instead of words as well, this would also better represents everyday situations, where attention is drawn to visual food cues in the environment and saccades are made towards salient cues. Combining this with fMRI, or electrophysiological measures for better temporal precision to disentangle the separate steps in attentional processes, would give better insight in whether and how attentional control would underlie the benefits of MBIs on eating behaviors.

With regard to the subjects, special attention should be paid to the motivation of subjects to change their eating behaviors and to actively participate in the trainings, including homework. Therefore, including questionnaires on motivation and expectations, as well as indications of time spent on homework and actively participating in the training sessions, could give insight in the role of these parameters.

Together, these adjustments would help to minimize most of the discussed limitations of our study, elucidating whether this may have influenced our findings.

Additionally, alternative underlying mechanisms of MBIs in relation to increases in healthy eating behaviors should be explored further. Awareness of bodily sensations, which also covers internal cues of hunger and satiety, is not easy to measure. The Observe subscale of the Five Facets Mindfulness Questionnaire (FFMQ; Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006) does represent general awareness of internal and external sensations. However, it does not exclusively measure internal bodily sensations and does not specifically focus on internal cues related to eating. Therefore it is not very suited to assess the awareness of these internal cues. Developing a different method to measure this, such as scoring the number of times the subject is aware of hunger during the day, might help to gain insight in the role of enhanced awareness of bodily sensation in increasing healthy eating behaviors.

Emotional eating can be measured with questionnaires, such as the Dutch Eating Behavior Questionnaire (DEBQ; van Strien, Frijters, Bergers, & Defares, 1986) and the Emotional Eating Scale (EES; Arnow, Kenardy, & Agras, 1995), as well as with experimental paradigms such as used by Evers, Stok, & de Ridder (2010). Future research could use these methods to clarify whether emotional eating is changed by MBIs and whether this then underlies the changes in healthy eating behaviors.

Lastly, it will be interesting to further explore the role of changes in acceptance. Again, questionnaires seem the best way to assess changes in acceptance. This could then be related to whether healthy eating behaviors do increase after an MBI and whether acceptance plays a role in the outcomes.

Thus, future research is needed to clarify the current findings and explore alternative working mechanisms of MBIs underlying the enhancement of healthy eating behaviors.

Conclusion

We did not find significant changes in attentional control on the behavioral or neural level from before to after a Mindful Eating intervention, implying that attentional control does not underlie the beneficial effects of MBIs on healthy eating behaviors as described in the existing literature. Investigating other mechanisms of change might help to elucidate how MBIs are able to increase heathy eating behaviors. Moreover, because our result is a null-finding, future research is needed to clarify whether possible limitations of our study prevented us from finding an effect, notwithstanding the proper design and use of methods within our study. This study, together with future research that builds on the considerations resulting from this study, will help us understand how MBIs bring about their positive effects on healthy eating behaviors and how we can optimize interventions to help people change unwanted eating habits effectively.

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