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The effect of a brief mindfulness intervention on perception of bodily signals of satiation and hunger

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ABSTRACT

An increasing number of studies investigate the effects of mindfulness on food intake and weight outcomes, while the underlying mechanisms by which mindfulness exerts its effects have received less attention. We conducted two pre-registered studies to shed light on the frequently proposed yet largely understudied hypothesis that mindfulness improves awareness of bodily signals of satiation and hunger. We assessed the ability to perceive the onset of bodily signals of satiation with the two-step water load test (Study 1) and the ability to perceive the onset of bodily signals of hunger with the preload test (Study 2). A brief mindfulness exercise (body scan) did not impact the perception of satiation but improved the ability to perceive bodily signals of hunger. After the consumption of a standardized preload, participants in the two experimental conditions felt equally satiated; nevertheless, those in the mindfulness condition perceived the onset of hunger 18min earlier than those in the control condition and this effect persisted also in the presence of control variables. These findings together suggest that even a single and short mindfulness exercise can improve perception of hunger signals substantially, while more intensive mindfulness training may be needed to impact perception of satiation signals.

1. Introduction

Mindfulness has received increasing attention in the domain of eating regulation and weight management over the last decades. Mindfulness-based interventions have been found to reduce dysfunctional eating behaviours (e.g., binge eating, emotional eating, and external eating) (Carrière, Khoury, Günak, & Knäuper, 2018; O'Reilly, Cook, Spruijt-Metz, & Black, 2014), food intake (Tapper, 2017), and weight (Olson & Emery, 2015). Strikingly, even brief mindfulness exercises seem to have positive effects on physical, psychological, and behavioural outcomes (Heppner & Shirk, 2018; Howarth, Smith, Perkins-Porras, & Ussher, 2019). Considerably less attention has been paid, however, to the underlying mechanisms by which mindfulness exerts these effects. Several mechanisms have been proposed such as enhancement of episodic memory of the eating episode, reduction in eating automaticity, enhancement of sensory-specific satiation, increased awareness of emotional and external cues of eating, and increased awareness of bodily sensations of hunger and satiation (Tapper, 2017; Vanzhula & Levinson, 2020; Warren, Smith, & Ashwell, 2017). Yet only few studies have tested these mechanisms (see Tapper, 2017 for an overview).

In particular, there is scarce evidence on the effect of mindfulness on awareness of bodily sensations or hunger and satiation (Vanzhula & Levinson, 2020). Mindfulness-based interventions have been found to improve awareness of internal hunger and satiety cues, as measured with self-reports that are administered before and after the intervention (Warren et al., 2017). Nevertheless, it is possible that this improvement is mainly due to a demand effect because cultivation of awareness and responsiveness to such cues is a core intervention component in these studies. Additional insights come from experimental research in the field of interoception. Interoception refers to the perception of the physiological condition of the body (Craig, 2003) and can be seen as a broad domain that includes, among other systems, awareness of eating-related bodily sensations. Evidence from fMRI studies indicate that mindfulness impacts areas of the brain that are related to interoception, thereby increasing awareness of the internal state of the body (Farb, Segal, & Anderson, 2013; Ives-Deliperi, Solms, & Meintjes, 2011). Similar results have been reported by studies that use self-report measures of interoceptive awareness (e.g., the Multidimensional Assessment of Interoceptive Awareness - MAIA) (De Jong et al., 2016; Fissler et al., 2016) or behavioural measures of interoceptive accuracy (e.g., heartbeat detection task) (Fischer, Messner, & Pollatos, 2017), although evidence is less

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consistent for the latter (Ma-Kellams, 2014). To our knowledge no study has investigated the effect of mindfulness on abdominal visceral interoception (or gastric interoception as is commonly referred to), which is the most relevant interoceptive modality for eating-related sensations among the interoceptive modalities known for the various body systems (cardiac, respiratory, skin, etc.). This is an important gap given that different body systems tap into distinct neural processes (Baranauskas, Grabauskaite, & Griskova-Bulanova, 2017) and different measures of interoceptive accuracy do not necessarily correlate with each other (Ferentzi et al., 2018).

While this body of evidence provides preliminary support for the idea that mindfulness improves perception of bodily signals of hunger and satiation, to our knowledge only one study has examined the effect of mindful attention to the body on satiety perception, i.e., feelings of fullness at the post-meal interval. Van de Veer, van Herpen, and van Trijp (2016) found that participants who ate a low-caloric preload felt less full than those who ate a high-caloric preload only after having performed a brief body scan exercise, while no difference was observed in reported sensations by participants who focussed their attention to an object in the environment or those who conducted a filler task (control group). These results suggest that mindful attention to the body can improve the perception of satiety during the post-meal interval. Yet, the effect of mindfulness on perception of satiation and hunger remains unknown.

In this paper, we present two experimental studies that we conducted to assess the effect of mindfulness, specifically a brief body scan exercise, on the ability to perceive bodily signals of satiation and hunger. In Study 1, we used the two-step Water Load Test (WLT) (Van Dyck et al., 2016) to measure the ability to perceive the onset of bodily signals of satiation, operationalized as the percentage of stomach capacity that one needs to fill with water to perceive the first signal of satiation (referred to as satiation threshold (Van Dyck et al., 2016)). In Study 2 we conducted a standard preload test (Blundell et al., 2010) to measure how much time it takes one to perceive the onset of bodily signals of hunger after ingestion of a standardised preload (referred to as hunger threshold for correspondence with Study 1). Because we were particularly interested in the perception of bodily signals, we made several efforts to distinguish the physical component of satiation and hunger from cognitive components that also underlie these processes. By using water in Study 1 we bypassed the effects of cognitive factors that accompany the ingestion of food (e.g., sensory-specific satiation, satiation expectations, restrained eating tendencies) and restricted the process of satiation to gastric distention, or more accurately, gastro-intestinal distention since water empties quickly from the stomach to the intestine (Murray, Eddy, Bartoli, & Paul, 1994). After all, it has been shown that volume rather than energy content determines feelings of satiation (Goetze et al., 2007; Rolls, Bell, & Waugh, 2000). In Study 2 it was not possible to rule out the cognitive (mental) component of hunger (i.e., the tendency to think about food and eating despite not being physically hungry) by the design. Therefore, we measured and controlled for this in the analysis because cognitive elaboration with food can induce an attention bias towards food (Higgs, Dolmans, Humphreys, & Rutters, 2015), which might accelerate the perception of hunger. Furthermore, in this research we controlled for individual differences in trait sensitivity to physiological signals of satiation and hunger (Palascha, Van Kleef, De Vet, & Van Trijp, 2020a; Palascha, Van Kleef, De Vet, & Van Trijp, 2020b), an important factor that has been overlooked in previous studies (Tapper, 2017).

We hypothesized that individuals who conduct a short body scan exercise (mindfulness condition) achieve a lower mean satiation threshold (i.e., they need to fill a smaller percentage of their stomach capacity with water to perceive their first signal of satiation) (Study 1) and a lower mean hunger threshold (i.e., they need less time to perceive their first signal of hunger after consumption of a standardized preload) (Study 2) compared with individuals who conduct a filler task (control condition). The studies were pre-registered (Study 1: https://osf.io/har5x; Study 2: https://osf.io/2px4a)[1] and were pre-approved by the Social Sciences Ethics Committee of Wageningen University & Research. A written consent was obtained from all participants at the beginning of each study. The data of this research can be found in the Supplementary material. The data of each study's control group were also used to address a different research question (i.e., construct validity of self-report measures of trait sensitivity to satiation and hunger) that is discussed in Palascha, van Kleef, de Vet, & van Trijp (2021) (Manuscript under review).

2. Study 1

2.1. Methods

2.1.1. Participants

Posters, flyers, emailing lists, social media, and a research agency were used to recruit participants in Wageningen, the Netherlands. Exclusion criteria included any type of diabetes, any type of gastrointestinal diseases (including mild conditions, e.g., heartburn, dyspepsia, bloating, irritable bowel syndrome), hypertension, cardiovascular diseases, diseases of the respiratory system, mental illnesses, eating disorders, history of bariatric surgery, use of medication that is known to affect appetite and weight, pregnant and lactating women. Only Dutch people who said they adequately understand English (i.e., scored three or higher on a scale ranging from 1 = "not well at all" to 5 = "extremely well") were eligible because the study's main language was English but the experimental manipulation was conducted in Dutch. We aimed to recruit at least 240 participants in total. The sample size was decided in an auxiliary manner. First, we calculated the required sample size for the control group (n = 120), which would be used to address a research question that is addressed in Palascha et al. (2021) (Manuscript under review). This sample size was doubled so that a second arm (mindfulness group) of equal size could be recruited. After exclusion of 11 participants who failed to comply with the instructions for preparation (mentioned below) and one participant who had been subjected to the same experimental manipulation in the past, data from 226 participants remained for analysis (57 males, 169 females). Average age was 31.9 years (SD = 15.6) and average Body Mass Index (BMI) was 23.3 kg/m^2 (SD = 3.4) (3% underweight, 71% normal weight, 21% overweight, 3% obese, 2% missing). Ten participants (4%) were dieting for weight-loss at the time of the study.

2.1.2. Experimental design and manipulation

A quasi experimental design was used in this study. Participants were assigned to one of two experimental conditions such that the following criteria were met in order: 1. no participant had been previously exposed to the same experimental condition (participants could join both Studies 1 and 2, which were conducted in parallel and used the same experimental manipulation) and 2. experimental conditions had the same ratio of males/females during the course of the study. In the mindfulness condition, participants listened to an audio fragment that instructed them to perform a body scan exercise (4.19min). This manipulation aimed to direct participants' attention to various parts of their body and make them aware of their bodily sensations. In the control condition, participants listened to a neutral audio fragment about tourism

[1] During data collection and analysis we deviated from the pre-registration on the following points. 1. Study's 2 eligibility criterion for age was adjusted from 18 to 25 to 18–29 to allow for the timely completion of data collection. 2. We did not control the main analyses for extreme response style because there was no theoretical reason to believe that this measure would account for variance in satiation and hunger thresholds. 3. Sensations reported after the preload were not included as control variables in the main analysis in Study 2 to prevent multicollinearity problems since those sensations could vary systematically with hunger threshold.

(3.49min). The audio fragments were pre-existing material developed by Van de Veer et al. (2016). Participants evaluated the audio fragment they listened to in terms of liking (1 = "Dislike a lot" to 5 = "Like a lot"), length (1 = "Too short" to 5 = "Too long"), pace of narrator (1 = "Extremely slow" to 5 = "Extremely fast"), and interestingness (1 = "It did not catch my interest at all" to 5 = "It caught my interest a lot").

2.1.3. Measures

2.1.3.1. Satiation threshold. Satiation threshold was measured with the two-step WLT (Van Dyck et al., 2016). Participants were given a non-transparent 1.5L bottle of water and a straw and were asked to drink ad libitum until they could perceive their first sign of satiation (T1). The instructions were slightly adapted from Van Dyck et al. (2016) as follows, to make it explicit that participants should report their *first* signal of satiation (not *a* signal): 'We ask you to drink water with the straw until you perceive your *first* sign of satiation. By satiation we mean the comfortable sensation you perceive when you have eaten a meal and you have eaten enough, but not too much. You have 5 min to complete this task. Start drinking now.' Upon completion of the first drinking round, the bottle was replaced by a new identical bottle and participants were asked to continue drinking until reaching their maximum stomach capacity (T2). The instructions were: 'We now ask you to drink again using the straw. Please continue drinking until your stomach is completely full, that is, entirely filled with water. You have 5 min to complete this task. Start drinking now.' The following measures were calculated: 1. water volume (in ml) required to perceive the first sign of satiation (Intake Satiation), 2. additional water volume required to produce maximum fullness (Intake Fullness), 3. total water volume ingested (Intake Total), and 4. percentage of Intake Satiation to Intake Total (Satiation threshold).

2.1.3.2. Trait sensitivity to physiological signals of satiation. The sensitivity to physiological signals of satiation subscale (SS) of the Multidimensional Internally Regulated Eating Scale (MIRES) was used to measure the ability to perceive and interpret the signals that the body naturally generates in response to satiation (Palascha et al., 2020a). The scale consists of nine items administered with 7-point scales (1 = "Completely untrue for me" to 7 = "Completely true for me"). Cronbach's alpha was .89 and items ratings were averaged to an overall score that was used as control variable in the main analysis.

2.1.3.3. Sensations of satiation and hunger. Participants reported their subjective sensations of hunger and satiation using a list of commonly reported terms identified from prior research (Guss, Kissileff, Booth, & Nolan, 2000; Monello & Mayer, 1967; Murray & Vickers, 2009). Responses were provided on 100 mm visual analogue scales (VAS) (0 = "Not at all" to 100 = "As much as I can imagine"). Hunger sensations were assessed at baseline (T0) and satiation sensations were assessed at baseline and after each drinking round of the WLT (T1 and T2). The items were grouped using the following structure, as indicated by Principal component Analysis (PCA) (see Supplementary material): Hunger sensations (weakness, rumbling stomach, lack of concentration, lightheaded, irritated, nervous, tense), Early sensations of satiation (full stomach, satisfied, relaxed, happy), Late sensations of satiation (heavy feeling, feeling bloated, discomfort, nausea, regret, disgust with yourself). We calculated a mean score for each group of items and each time point and used those scores to compare how the two experimental groups experienced the WLT. Furthermore, we used the satiation sensations to assess participants' concept states of comfortable satiation and complete fullness to control for differences in interpretation of the WLT instructions in the main analysis. Specifically, participants were asked "Imagine you have just eaten a meal and you have eaten enough but not too much. How would you describe this sensation in terms of the following factors?" (Concept T1) and "Now imagine you have just eaten a meal until your stomach is completely full. How would you describe this sensation in terms of the following factors?" (Concept T2). Participants also indicated how frequently they stop eating once they reach comfortable satiation (Frequency Satiation) and how frequently they reach complete fullness (Frequency Fullness) (1 = "Never" to 5 = "Always") under natural circumstances.

2.1.3.4. Disposition to eat. Participants were presented with two images that each contained 20 items of a food product: digestive biscuits and crackers with cheese, respectively. They were asked to click on the images to highlight how many quarters (for digestive biscuits) and how many halves (for crackers with cheese) they would eat if each food offered by itself at that moment (Booth, 2009). Disposition to eat (DTE) was measured to assess the impact of the WLT on appetite for food. For each time point (T0, T1, T2), we calculated an indicator of DTE something sweet (DTE sweet) by adding the quarters of digestive biscuit and an indicator of DTE something savoury (DTE savoury) by adding the halves of crackers with cheese.

2.1.3.5. Demographic and control variables. Gender, age (years), weight (kg), height (cm), dieting for weight loss (Yes/No), smoking (Yes/No), last night's sleep duration (hours), physical activity (1 = "Not active at all" to 5 = "Extremely active"), and frequency of breakfast consumption (1 = "Never" to 5 = "Always") were also reported. In addition, participants indicated what time they last ate and drank something and whether there was any medical, ethical, religious, or other personal reason that prevented them from eating digestive biscuits and crackers with cheese (Yes/No). These measures were used to characterize the sample, to compare the experimental groups, to check participants' compliance with the instruction for preparation, and/or to be used as control variables in the main analysis.

2.1.3.6. Other measures. Extreme response style (Greenleaf, 1992) and interoceptive awareness (Mehling et al., 2012) were also measured to address a research question that is discussed in Palascha et al. (2021) (Manuscript under review) and are not mentioned further in this paper.

2.1.4. Procedure

Interested individuals filled in an online eligibility questionnaire that also assessed trait sensitivity to physiological signals of satiation. Eligible participants arrived at the laboratory between 9:00 and 11:30, having remained abstinent from eating (including caloric drinks) for at least 3 h prior to their session, from drinking (including water, coffee, or tea) for at least 2 h prior to their session, from intense physical activity in the morning of their session, and from alcohol consumption the day prior to their session. Thus, participants arrived at the same physical state and a series of situational factors that influence the processes of gastric accommodation and gastric emptying were controlled for (Costa, Snipe, Kitic, & Gibson, 2017; Hellmig et al., 2006). To check participants' compliance with the instructions we asked them verbally upon arrival but also calculated how much time had passed since they had last eaten and drank something. First, we assessed how participants interpret the instructions of the WLT by asking them to imagine a typical consumption situation in which they feel comfortably satiated (Concept T1) or completely full (Concept T2) and to rate how they would feel in each case using a list of satiation sensations. Then, we assessed their baseline (T0) hunger and satiation sensations and disposition to eat, followed by the experimental manipulation. Participants then conducted the WLT and reported their satiation sensations and disposition to eat after the first (T1) and after the second (T2) drinking round. The remaining self-reports and control measures were assessed at the end of the study. Participants were rewarded with snacks and shopping vouchers and received a debriefing email upon completion of data collection.

2.2. Analysis

Statistical analysis was performed in SPSS 26. Multiple linear regression analysis was conducted with satiation threshold as dependent variable and experimental condition as independent variable with and without control variables. The assumptions of normality and homoscedasticity were met; thus, the results of this study can be assumed to be generalizable beyond the study's sample (Field, 2009). Furthermore, repeated measures ANOVA was used to assess changes in reported sensations of satiation and disposition to eat during the study. Experimental condition was entered as a between-subjects factor in these analyses and pairwise comparisons with Bonferroni adjustment were used to assess differences between the various time points (alpha was set at $\alpha = .02$). Differences in baseline characteristics and control variables between experimental conditions were assessed with independent samples t-tests. Because we expected to not reject the null hypothesis in these analyses, we also conducted equivalence tests in R to confirm that differences between experimental conditions were significantly small ($-0.5 < D < 0.5$), or in other words, significantly equivalent to zero. Finally, Pearson's chi square tests indicated whether the experimental conditions were comparable in terms of distribution of nominal variables (e.g., males/females).

2.3. Results

2.3.1. Randomization check

No significant differences were observed between experimental conditions in age, BMI, SS, sleep duration, physical activity, baseline sensations of hunger and satiation, baseline disposition to eat, concept states of satiation and fullness, and frequency of reaching the concept state of fullness (Table 1). Equivalence tests further showed that these differences were significantly equivalent to zero. The distributions of males/females (χ^2 (1) = .02, p = 1.00), dieters/non-dieters (χ^2 (1) < .001, p = 1.00), and smokers/non-smokers (χ^2 (1) = .35, p = .77) also did not differ significantly between experimental conditions. The control group reported significantly lower frequency of breakfast consumption (t (224) = −2.50, p = .01) and lower frequency of stopping eating upon experience of comfortable satiation (t (224) = −2.04, p = .04) compared with the mindfulness group. Finally, the control audio fragment was liked significantly less than the mindfulness audio fragment (t (224) = −2.56, p = .01) and was also found to be significantly less interesting (t (224) = −3.46, p = .001), lengthier (t (224) = 5.75, p < .001), and slower in terms of pace of narration (t (224) = −4.65, p < .001). Inclusion of these variables in the multiple linear regression model did not impact the results.

2.3.2. Hypothesis testing

Multiple linear regression analysis yielded a non-significant effect of Condition on satiation threshold both in the absence (B = -.16, SE = 1.81, p = .93) and presence of control variables (B = -.67, SE = 1.82, p = .72) (Table 2). The interaction between SS and Condition was non-significant and was not included in the final model because we had not formulated an a priori hypothesis for this term. The volumes ingested at each drinking round of the WLT are shown in (Table 3).

2.3.3. Changes in sensations and disposition to eat

Repeated measures ANOVA with early sensations of satiation yielded a non-significant Time x Condition interaction effect (F (2,223) = .69, p = .50, η^2 = .01) and a significant Time effect (F (2,223) = 138.36, p < .001, η^2 = .55). Pairwise comparisons indicated that early sensations increased significantly at T1 (Mdiff = 18, SDdiff = 1, p < .001) but did not differ significantly between T1 and T2 (Mdiff = −2, SDdiff = 1, p = .12) (Fig. 1). In turn, a non-significant Time x Condition interaction effect (F (2,223) = .28, p = .76, η^2 = .002) and a significant Time effect (F (2,223) = 316.39, p < .001, η^2 = .74) were evident for late sensations

Table 1
Characteristics of participants in the control and mindfulness condition (Study 1).

	t	*p*	M (SD)	
			Control condition	Mindfulness condition
Age (years)	.19	.85	32.1 (15.6)	31.7 (15.6)
BMI (kg/m^2)	-.09	.93	23.2 (3.5)	23.3 (3.2)
SS (scales 1–7)	-.69	.49	6 (1)	6 (1)
Sleep duration (hours)	.19	.85	8 (1)	8 (1)
Physical activity (scale 1–5)	-.57	.57	3 (1)	3 (1)
Frequency of breakfast consumption (scale 1–5)	−2.50	.01	5 (1)	5 (1)
Hunger sensations T0 (scales 1–100)	.55	.59	23 (18)	21 (16)
Satiation early sensations T0 (scales 1–100)	.20	.84	38 (18)	37 (18)
Satiation late sensations T0 (scales 1–100)	-.43	.67	10 (12)	11 (13)
DTE sweet T0 (# of quarters)	-.03	.98	13 (10)	13 (9)
DTE savoury T0 (# of halves)	−1.54	.13	4 (3)	5 (4)
Satiation early sensations Concept T1 (scales 1–100)	−1.83	.07	68 (18)	72 (18)
Satiation late sensations Concept T1 (scales 1–100)	-.37	.71	15 (14)	16 (15)
Satiation early sensations Concept T2 (scales 1–100)	-.43	.67	60 (19)	61 (19)
Satiation late sensations Concept T2 (scales 1–100)	1.46	.15	51 (23)	47 (21)
Frequency Satiation (scale 1–5)	−2.04	.04	3 (1)	4 (1)
Frequency Fullness (scale 1–5)	-.47	.64	2 (1)	2 (1)
Audio fragment: Liking (scale 1–5)	−2.56	.01	3 (1)	4 (1)
Audio fragment: Length (scale 1–5)	5.75	<.001	4 (1)	3 (1)
Audio fragment: Pace of narrator (scale 1–5)	−4.65	<.001	3 (1)	3 (1)
Audio fragment: Interesting (scale 1–5)	−3.46	.001	3 (1)	4 (1)

SS: Sensitivity to physiological signals of satiation, BMI: Body Mass Index, DTE: Disposition to eat.

Table 2
Multiple linear regression analysis predicting satiation threshold.

	B	SE	*t*	*p*	R^2
Crude model					
Condition	-.16	1.81	-.09	.93	<.001
Adjusted model					
Condition	-.67	1.82	-.37	.72	.06
Age	-.14	.08	−1.80	.07	
Gender	4.13	2.22	1.86	.07	
BMI	.13	.32	.41	.68	
SS	1.37	1.11	1.23	.22	
Dieting	−1.61	4.49	-.36	.72	
Satiation early sensations Concept T1	-.01	.06	-.08	.94	
Satiation late sensations Concept T1	.09	.07	1.23	.22	
Satiation early sensations Concept T2	.05	.06	.92	.36	
Satiation late sensations Concept T2	-.05	.05	-.85	.40	

SS: Sensitivity to physiological signals of satiation, BMI: Body Mass Index.

[2] Water can have a temporary satiating effect as shown in Study 1; nevertheless, small amounts of water are unlikely to impact satiety since water empties quickly to the intestines (Murray et al., 1994). Therefore, in this study participants were allowed to drink water in anticipation of the hunger signal.

Table 3
Descriptive statistics for the WLT data.

	Control condition ($n_1 = 113$)		Mindfulness condition ($n_2 = 113$)		Total sample (N = 226)		
	M	SD	M	SD	M	SD	Range
Intake to satiation (ml)	339	148	353	179	346	164	41–959
Intake to fullness (ml)	413	192	410	212	412	202	46–1211
Total intake (ml)	752	264	763	313	758	289	141–1760
Satiation threshold (%)	46.0	12.9	46.2	14.0	46.1	13.4	11.4–79.7

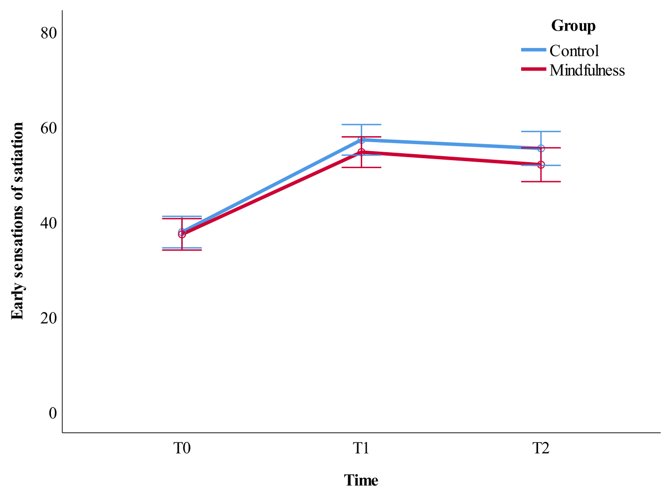

Fig. 1. Early sensations of satiation - Study 1 (error bars represent 95% CI).

of satiation. Late sensations increased significantly both at T1 (Mdiff = 5, SDdiff = 1, $p < .001$) and at T2 (Mdiff = 28, SDdiff = 1, $p < .001$) (Fig. 2). Furthermore, a non-significant Time x Condition interaction ($F(2,220) = 1.89$, $p = .15$, $\eta^2 = .02$) and a significant Time effect ($F(2,220) = 221.47$, $p < .001$, $\eta^2 = .67$) were observed for DTE sweet. DTE sweet reduced significantly at T1 (Mdiff = −6, SDdiff = 1, $p < .001$) and at T2 (Mdiff = −4, SDdiff = .2, $p < .001$) (Fig. 3). Similar results were obtained for DTE savoury [Time x Condition: $F(2,207) = 2.09$, $p = .13$, $\eta^2 = .02$; Time effect: $F(2,207) = 279.22$, $p < .001$, $\eta^2 = .64$]. DTE savoury decreased significantly at T1 (Mdiff = −2, SDdiff = .1, $p < .001$) and at T2 (Mdiff = −2, SDdiff = .1, $p < .001$) (Fig. 4).

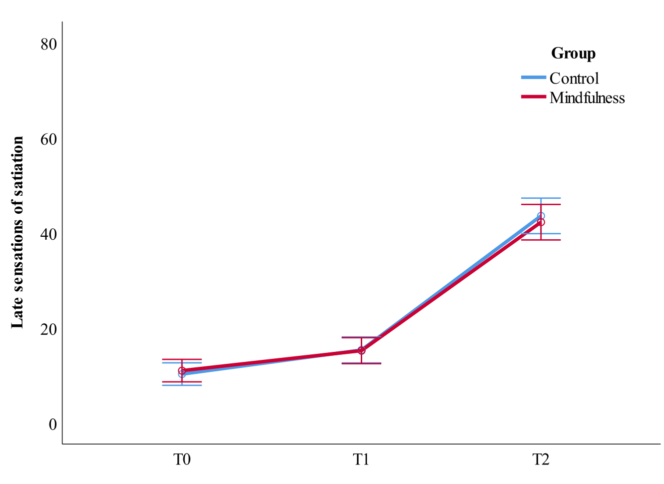

Fig. 2. Late sensations of satiation - Study 1 (error bars represent 95% CI).

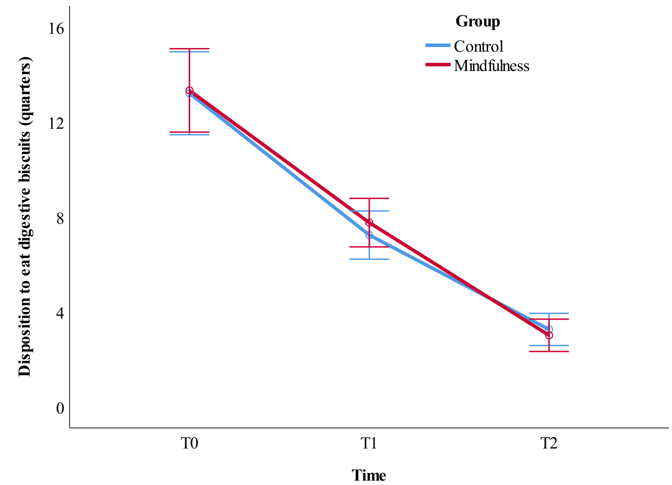

Fig. 3. Disposition to eat something sweet - Study 1 (error bars represent 95% CI).

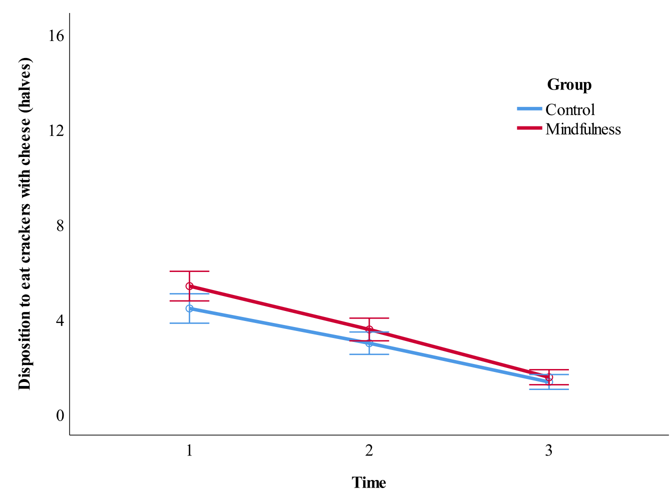

Fig. 4. Disposition to eat something savoury - Study 1 (error bars represent 95% CI).

2.4. Discussion

In this study, a brief mindfulness exercise was not effective in making individuals more perceptive of their bodily signals of satiation. Participants in the two experimental conditions manifested similar satiation thresholds and experienced similar patterns of satiation sensations and disposition to eat over the course of the study. The increase in satiation sensations and decrease in disposition to eat that were documented after the two drinking rounds of the WLT indicate that water was effective in inducing satiation and fullness.

3. Study 2

3.1. Methods

3.1.1. Participants

A relatively homogeneous sample of Dutch females between 18 and 29 years old was recruited in this study to minimize variability in the satiating effect of the preload. The same recruitment means, eligibility criteria, and rationale for sample size calculations as in Study 1 were used. In addition, individuals who had medical (e.g., allergy, intolerance), ethical, religious, or other personal reasons that prevented them from eating any of the study foods were excluded. After excluding three participants who had incomplete data, two who did not finish the preload, and 14 who failed to comply with the instructions for preparation, data from 217 participants remained for analysis. Participants' average age was 22.0 years (SD = 2.1) and average BMI was 22.0 kg/m^2 (SD = 2.4) (4% underweight, 89% normal weight, 7% overweight, 1% obese). Six participants (3%) were dieting for weight-loss at the time of the study.

3.1.2. Experimental design and manipulation

Same as Study 1.

3.1.3. Measures

3.1.3.1. Hunger threshold. Hunger threshold was measured with the preload test (Blundell et al., 2010). Participants were offered a standardized lunch preload (M = 563 kcals, SD = 13 kcals) and were asked to consume it entirely. The preload consisted of a sandwich with hummus and cucumber, a raisin bun, a small carton of orange juice (200 ml), and a cup of water (125 ml). Participants noted 1. the exact time of finishing the preload in the laboratory (T1) and, 2. the exact time of perceiving their first signal of hunger under natural circumstances (T2). By subtracting the two times, we calculated the hunger threshold in minutes. Participants were instructed to not eat or drink anything between the two time points. The instructions were as follows: "The researcher will now give you a sealed envelope that includes a questionnaire. We ask you to open this envelope the moment you perceive a first sign of hunger. By hunger we mean the sensation you perceive when you haven't eaten for some time and your stomach is ready to receive food. We request that you don't eat or drink anything (except for water[2]) before you reach this state".

3.1.3.2. Trait sensitivity to physiological signals of hunger. We assessed the ability to perceive and interpret the signals that the body naturally generates in response to hunger with the sensitivity to physiological signals of hunger (SH) subscale of MIRES (Palascha et al., 2020a), which is consisted of nine items administered with 7-point scales (1 = "Completely untrue for me" to 7 = "Completely true for me"). Cronbach's alpha was .85 in this study and the average score was used as control variable in the main analysis.

3.1.3.3. Sensations of hunger and satiation. Like in Study 1, participants provided repeated ratings of their hunger and satiation sensations at baseline (T0), T1, and T2. The hunger sensations were also used to rate participants' concept state of hunger (Concept T2) as a means of controlling the main analysis for individual differences in interpretation of the instructions used to report hunger threshold. Specifically, participants were asked "Imagine that you haven't eaten for some time and your stomach is ready to receive food. How would you describe this sensation in terms of the following factors?". Participants also indicated how frequently they initiate eating as soon as they reach this state under natural circumstances (Frequency Hunger) (1 = "Never" to 5 = "Always"). In this study the items were grouped as follows as indicated by PCA (see Supplementary material): Early sensations of hunger (empty stomach, rumbling stomach), Late sensations of hunger (weakness, lack of concentration, lightheaded, irritated, tense, nervous), Early sensations of satiation (satisfied, happy, relaxed), and Late sensations of satiation (heavy feeling, feeling bloated, nausea, discomfort, regret, disgust with yourself). A mean score was calculated for each group of items and each time point.

3.1.3.4. Disposition to eat. The same procedure as in Study 1 was used. Chocolate chip cookies (in quarters) and salty crackers (in halves) were used to measure DTE sweet and DTE savoury, respectively.

3.1.3.5. Hunger as a mental state. A single item ("Since you left the lab, to what extent did you think about eating despite not being physically hungry?") administered on a 100 mm VAS (0 = "I did not think about eating at all" and 100 = "I was constantly thinking about eating") was used to measure hunger as a mental state and was added as control variable in the main analysis.

3.1.3.6. Restrained eating. To measure one's intention to restrict food intake in order to control body weight we used the restrained eating (RE) scale of the Dutch Eating Behaviour Questionnaire (DEBQ) (Van Strien, Frijters, Bergers, & Defares, 1986), consisted of 10 items administered with 5-point frequency scales (1 = "Never" and 5 = "Very often"). Cronbach's alpha was .89 in this study and responses were averaged. RE was used as a control variable in the main analyses because the chronic tendency to restrict food intake could influence the ability to perceive physical sensations of hunger (Herman & Polivy, 1983; Murray & Vickers, 2009).

3.1.3.7. Demographic, control, and other measures. Same as Study 1.

3.1.4. Procedure

An online questionnaire included the study's eligibility criteria and the measure of trait sensitivity to physiological signals of hunger. Eligible participants joined a laboratory session between 13:00 and 15:30, after having refrained from eating (including caloric drinks) for at least 4 h prior to their session, from intense physical activity the morning of their session, and from alcohol consumption the day prior to their session. Instruction compliance was checked verbally but also computationally as in Study 1. First, participants reported their hunger and satiation sensations and disposition to eat at baseline (T0) and then performed the experimental manipulation. Then, they consumed the lunch preload and noted the exact time of ending the meal. Sensations of hunger and satiation and disposition to eat were reported after the preload (T1), followed by the control measures. Before leaving the laboratory, participants used the list of hunger sensations to rate their concept state of hunger (Concept T2) (in line with Study 1) and received a sealed questionnaire that they had to open and fill in by the moment they would perceive their first signal of hunger (T2). This questionnaire was used to report the time of hunger onset as well as hunger as a mental state, sensations of hunger and satiation, disposition to eat, and restrained eating. This questionnaire was returned by participants in person or by post and participants received a shopping voucher as a reward for their participation as well as a debriefing email upon completion of data collection.

3.2. Analysis

Same as Study 1. Four outliers were excluded for the assumptions of normality and homoscedasticity to be met. Thus, analysis was conducted with 213 participants. We only report results excluding the outliers, as otherwise the model is not appropriate for parametric analysis.

3.3. Results

3.3.1. Randomization checks

With the exception of SH, which was significantly higher in the control group ($t(211) = 2.20$, $p = .03$), non-significant differences were observed between the experimental conditions in terms of background characteristics (Table 4). Equivalence tests further indicated that all differences were significantly equivalent to zero. Likewise, the distribution of dieters/non-dieters ($\chi^2(1) = 2.78$, $p = .12$), and smokers/non-smokers ($\chi^2(1) < .001$, $p = 1.00$) did not differ significantly between experimental conditions. Finally, the control audio fragment was liked significantly less than the mindfulness audio fragment ($t(211) = -5.58$, $p < .001$) and was also found to be significantly less interesting ($t(211) = -4.74$, $p < .001$), lengthier ($t(211) = 6.84$, $p < .001$), and slower in

Table 4
Characteristics of participants in the control and mindfulness condition (Study 2).

	t	*p*	M (SD)	
			Control condition (n1 = 107)	Mindfulness condition (n2 = 106)
Age (years)	1.74	.08	22.2 (2.1)	21.7 (2.1)
BMI (kg/m^2)	−1.22	.22	21.8 (2.3)	22.2 (2.5)
SH (scales 1–7)	2.20	.03	6 (1)	6 (1)
RE (scales 1–5)	−1.12	.26	2 (1)	2 (1)
Sleep duration (hours)	.69	.49	8 (1)	8 (1)
Physical activity (scale 1–5)	-.18	.86	3 (1)	3 (1)
Hunger early sensations T0 (scales 1–100)	.27	.79	58 (23)	57 (22)
Hunger late sensations T0 (scales 1–100)	-.80	.42	25 (18)	27 (17)
Satiation early sensations T0 (scales 1–100)	1.27	.21	45 (19)	42 (17)
Satiation late sensations T0 (scales 1–100)	.01	.99	13 (13)	13 (11)
DTE sweet T0 (# of quarters)	−1.16	.25	13 (9)	14 (9)
DTE savoury T0 (# of halves)	-.96	.34	12 (8)	13 (8)
Hunger early sensations Concept T2 (scales 1–100)	.15	.88	69 (21)	68 (19)
Hunger late sensations Concept T2 (scales 1–100)	-.99	.32	33 (21)	35 (20)
Frequency Hunger (scale 1–5)	-.18	.85	4 (1)	4 (1)
Audio fragment: Liking (scale 1–5)	−5.58	<.001	3 (1)	4 (1)
Audio fragment: Length (scale 1–5)	6.84	<.001	4 (1)	4 (1)
Audio fragment: Pace of narrator (scale 1–5)	−3.41	.001	2 (1)	3 (1)
Audio fragment: Interesting (scale 1–5)	−4.74	<.001	3 (1)	3 (1)

SH: Sensitivity to physiological signals of hunger, BMI: Body Mass Index, RE: Restrained eating, DTE: Disposition to eat.

terms of pace of narration (t (211) = −3.41, p = .001). Inclusion of these variables in the regression model did not impact the results.

3.3.2. Hypothesis testing

The mean hunger threshold for the study participants was 176min (SD = 112). The effect of Condition on hunger threshold was significant (B = −18.32, SE = 8.22, p = .03) (Table 5). Participants in the mindfulness condition perceived the onset of hunger 18min earlier (on average) than participants in the control condition (Fig. 5) and this effect persisted also in the presence of control variables (B = −17.14, SE = 8.43, p = .04). Mental hunger was also a significant predictor of hunger threshold (B = −4.80, SE = 1.65, p = .004). The interaction between SH and Condition was non-significant and was not included in the final regression model because no a priori hypothesis had been formulated for this term.

Table 5
Multiple linear regression analysis predicting hunger threshold.

	B	SE	*t*	*p*	R^2
Crude model					
Condition	−18.32	8.22	−2.23	.03	.02
Adjusted model					
Condition	−17.14	8.43	−2.03	.04	.07
Age	.13	2.16	.06	.95	
BMI	1.09	1.87	.58	.56	
SH	.84	5.25	.16	.87	
Mental hunger	−4.80	1.65	−2.91	.004	
RE	4.02	5.70	.71	.48	
Dieting	−33.89	28.32	−1.20	.23	
Hunger early sensations Concept T2	.04	.24	.18	.86	
Hunger late sensations Concept T2	-.05	.23	-.22	.82	

SH: Sensitivity to physiological signals of hunger, BMI: Body Mass Index, RE: Restrained eating.

3.3.3. Changes in sensations and disposition to eat

Repeated measures ANOVA with early sensations of hunger yielded a non-significant Time x Condition interaction effect (F (2,210) = .80, p = .45, η^2 = .01) and a significant Time effect (F (2,210) = 658.83, p < .001, η^2 = .86). Pairwise comparisons indicated that early sensations of hunger reduced significantly at T1 (Mdiff = −51, SDdiff = 2, p < .001) and increased significantly at T2 (Mdiff = 38, SDdiff = 1, p < .001) (Fig. 6). Likewise, a non-significant Time x Condition interaction effect (F (2,210) = .08, p = .93, η^2 = .001) and a significant Time effect (F (2,210) = 164.87, p < .001, η^2 = .61) were evident for late sensations of hunger, which reduced significantly at T1 (Mdiff = −15, SDdiff = 1, p < .001) and increased significantly at T2 (Mdiff = 13, SDdiff = 1, p < .001) (Fig. 7).

Analysis with early sensations of satiation yielded a non-significant Time x Condition interaction effect (F (2,210) = .01, p = .99, η^2 < .001) and a significant Time effect (F (2,210) = 111.29, p < .001, η^2 = .52). Early sensations of satiation increased significantly at T1 (Mdiff = 20, SDdiff = 1, p < .001) and decreased significantly at T2 (Mdiff = −15, SDdiff = 1, p < .001) (Fig. 8). Finally, a marginally significant Time x Condition interaction effect (F (2,210) = 3.12, p = .05, η^2 = .03) and a significant Time effect (F (2,210) = 20.35, p < .001, η^2 = .16) were evident for late sensations of satiation. Analysis by time point showed no significant differences between experimental conditions (T0: F (1,212) < .001, p = .99, η^2 < .001; T1: F (1,212) = 1.25, p = .27, η^2 = .01; T2: F (1,212) = 1.80, p = .18, η^2 = .01) and sub-group analysis showed that in the Control condition late sensations of satiation increased significantly at T1 (Mdiff = 8, SDdiff = 2, p < .001) and decreased significantly at T2 (Mdiff = −8, SDdiff = 1, p < .001), while in the Mindfulness condition they increased significantly at T1 (Mdiff = 5, SDdiff = 1, p < .001) but did not decrease significantly at T2 (Mdiff = −4, SDdiff = 1, p = .03) (Fig. 9).

A non-significant Time x Condition interaction effect (F (2,207) = .32, p = .73, η^2 = .003) and a significant Time effect (F (2,207) = 187.05, p < .001, η^2 = .64) were observed for DTE sweet (Fig. 5). DTE sweet reduced significantly at T1 (Mdiff = −9, SDdiff = 1, p < .001) and increased significantly at T2 (Mdiff = 7, SDdiff = 1, p < .001) (Fig. 10). Similarly, there was a non-significant Time x Condition interaction (F (2,207) = .11, p = .89, η^2 = .001) and a significant Time effect (F

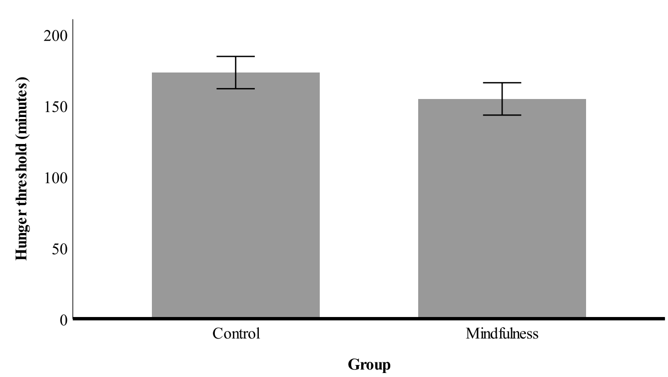

Fig. 5. Significant reduction in hunger threshold in the Mindfulness group compared with the Control group (error bars represent 95% CI).

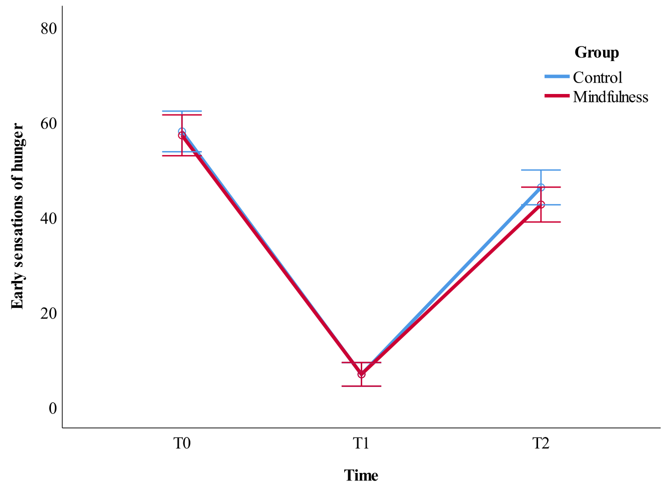

Fig. 6. Early sensations of hunger - Study 2 (error bars represent 95% CI).

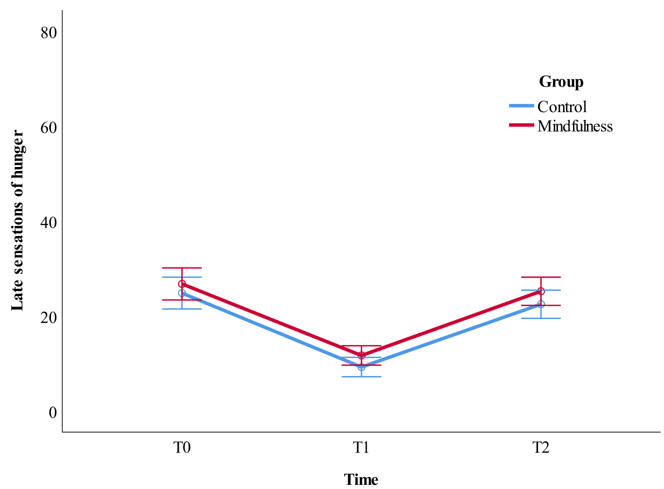

Fig. 7. Late sensations of hunger - Study 2 (error bars represent 95% CI).

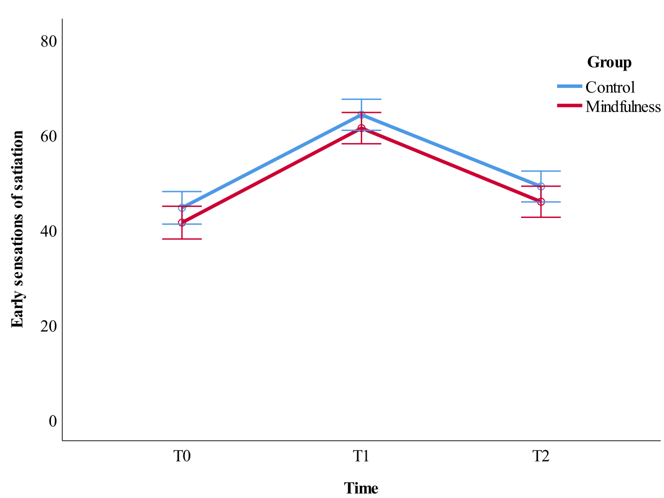

Fig. 8. Early sensations of satiation - Study 2 (error bars represent 95% CI).

(2,207) = 226.36, $p < .001$, $\eta^2 = .69$) for DTE savoury. DTE savoury decreased significantly at T1 (Mdiff = −9, SDdiff = 1, $p < .001$) and increased significantly at T2 (Mdiff = 6, SDdiff = .4, $p < .001$) (Fig. 11).

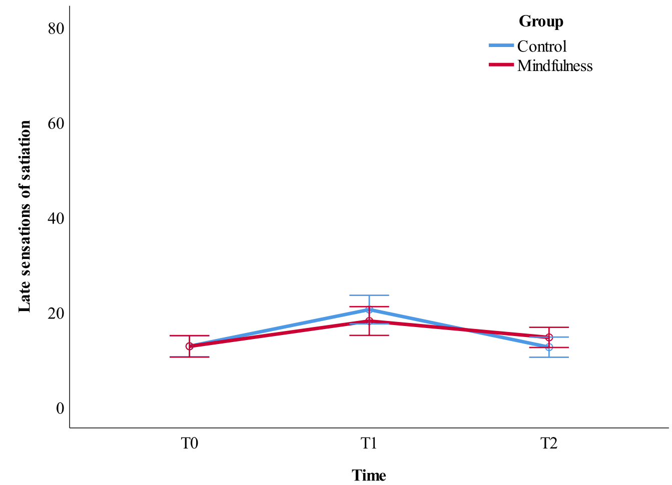

Fig. 9. Late sensations of satiation - Study 2 (error bars represent 95% CI).

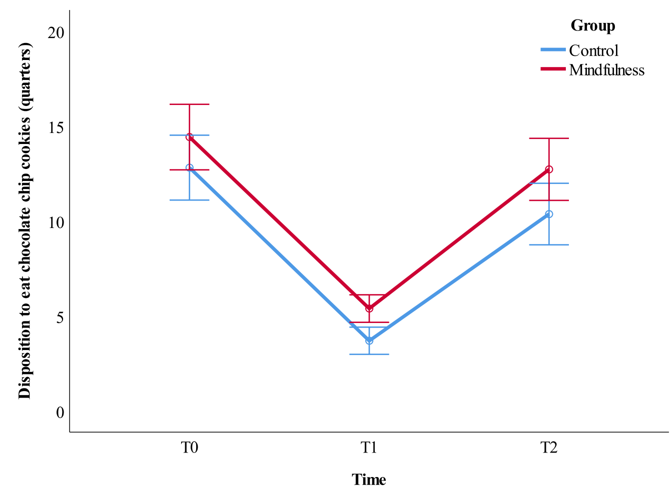

Fig. 10. Disposition to eat something sweet - Study 2 (error bars represent 95% CI).

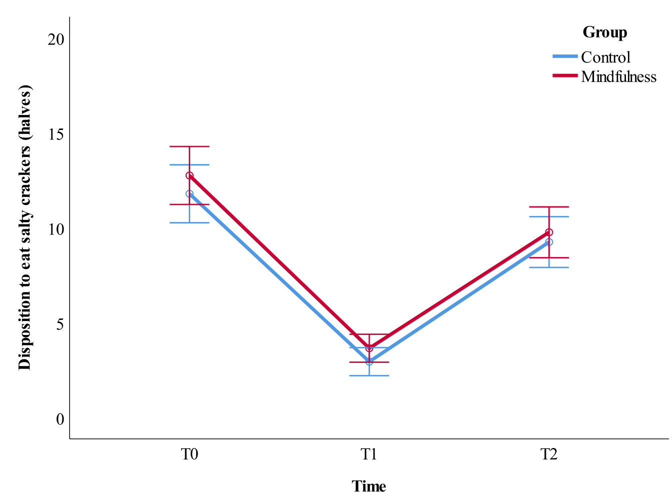

Fig. 11. Disposition to eat something savoury - Study 2 (error bars represent 95% CI).

3.4. Discussion

The results of this study show that mindfulness improves the ability to perceive bodily signals of hunger. Participants who conducted a brief body scan exercise prior to eating the preload perceived the onset of physical hunger 18min earlier than participants in the control condition. The general pattern of experienced sensations of hunger and satiation and disposition to eat was similar between experimental conditions, which suggests that participants in the mindfulness condition simply perceived the signal faster. In turn, the control group experienced a steeper decline in late sensations of satiation upon the onset of hunger, which means that a larger shift in experienced sensation had to take place for the control group to perceive the onset of hunger. Finally, reported sensations and disposition to eat changed in predictable ways over the course of the study in both experimental conditions, providing evidence that the preload was adequate to induce satiation at T1 but also that participants had indeed started feeling hungry when they reported the onset of hunger at T2.

4. General discussion

In this research we investigated the effect of mindfulness on the ability to perceive bodily signals of satiation and hunger, a largely understudied mechanism that might explain how mindfulness influences food intake and weight. We showed that a brief mindfulness exercise (body scan) did not have an impact on the ability to perceive bodily signals of satiation (Study 1), but it improved the ability to perceive bodily signals of hunger substantially (Study 2). These findings are in line with those observed by Van de Veer et al. (2016), who showed that the difference in fullness feelings after a small versus a large preload in participants who performed the body scan exercise was attributed to the reduction in fullness after the small preload and not to an increase in fullness after the large preload. These pieces of evidence together suggest that focusing attention on the body has a more pronounced effect in increasing awareness of hunger cues compared with satiation cues.

This contrast can be understood from the evolutionary perspective that suggests that humans are hardwired towards overeating as a means of storing energy reserves in anticipation of famine, a state frequently encountered by our early ancestors (Pinel, Assanand, & Lehman, 2000). In this light, it should be easier for humans to perceive hunger signals driving meal initiation than to perceive satiation signals driving meal termination. Therefore, more intensive practice with mindfulness may be required to improve the ability to perceive bodily signals of satiation than just a single and brief body scan exercise. In support to this, it has been found that time spent on meditation practice predicts reductions in binge eating episodes (Kristeller & Hallett, 1999) and correlates negatively with BMI and weight (Kristeller, Wolever, & Sheets, 2014).

Another explanation for the present findings is that mindfulness requires some time to take effect. This is supported by the fact that in Study 2, sensations of hunger and satiation after consumption of the preload did not differ between experimental conditions, and it was only at a later stage (anticipation of the hunger signal) that mindfulness exerted its effect. Evidence from prior literature supports this idea, since mindfulness has more pronounced effects on subsequent food intake (later in the day) than on immediate food intake (while mindfulness takes place or right after) (see Tapper, 2017 for a review).

Finally, it is also likely that mindfulness did not have a consistent effect on perception of satiation and hunger because a different setting was used in the two studies. In Study 1, participants' ability to perceive the onset of satiation was assessed in the laboratory, while in Study 2, perception of hunger onset was assessed under ecologically valid conditions. Therefore, it is possible that a ceiling effect occurred in the quiet environment of the laboratory where participants had ideal conditions for attending to their bodily sensations. Instead, in Study 2, environmental distractions likely made the task of attending to bodily sensations more challenging, thereby unveiling the effect of mindfulness.

The present work contributes to the existing literature in several important ways. First, this research provides the first comprehensive assessment of the effects of mindfulness on perception of bodily signals of satiation and hunger, while ruling out a series of cognitive confounders. Second, in this research we took into account individual differences in sensitivity to physiological signals of satiation and hunger, a factor that has been overlooked in prior research. Third, this is the first research that looked at the effect of mindfulness on abdominal visceral interoception (as measured with the WLT), thereby contributing to the growing body of evidence on the various interoceptive modalities.

The following limitations should be acknowledged for the present research. Trait mindfulness or prior experience with mindfulness practice were not taken into account in this research. Also, in Study 2 participants reported their hunger threshold in ecologically valid conditions, thus, several uncontrolled factors such as the level of physical exercise or environmental distractions might have influenced hunger threshold. The allocation to experimental conditions likely neutralized the effects of these confounders. However, it should be noted that the limitation of this study is at the same time its strength because the ecologically valid setting generates findings that are more directly generalizable (higher external validity). Also, as we discussed previously, this setting might have played a role in the manifestation of the mindfulness effect. Finally, this research is also limited by the fact that it did not assess potential underlying mechanisms by which mindfulness impacts the perception of bodily signals of satiation and hunger. For example, the effect of mindfulness could be explained by top-down processes (i.e., increased active attendance to bodily sensations), bottom-up processes (i.e., the sensation itself enters awareness more vividly), both, or other processes (e.g. related to memory).

More studies are certainly needed to establish whether and how mindfulness impacts the perception of bodily signals of satiation and hunger and, in turn, whether this translates to lower food intake and weight. In this research we paid attention only to the direct effect of mindfulness on perception, thus, future studies could assess perception and outcome measures within the same investigation in order to shed light on the full mediation model. In particular, it would be interesting to investigate whether the improved ability to perceive early signals of hunger and satiation helps individuals achieve a narrower control of their eating by initiating meals at early levels of hunger and ceasing meals at early levels of satiation. Evidence from self-reports support this assertion since sensitivity to physiological signals of hunger and satiation associates positively with self-efficacy in using those signals to determine when and how much to eat (Palascha et al., 2020a). Assuming this holds true, the results of the present research imply that mindfulness may trigger early meal initiation but not necessarily early meal termination, which could ultimately lead to increased food intake if meals become more frequent but not smaller. Therefore, mindfulness interventions should prioritize the perception of satiation signals before attempting to improve the perception of hunger signals. Preferably, a more intensive type of mindfulness training should be employed than just a single and brief body scan exercise and could possibly be combined with training individuals to stop eating before reaching complete satiation, which is associated with lower food intake (Fukkoshi, Akamatsu, & Shimpo, 2015). Finally, in this research (particularly in Study 1) we sacrificed external validity in order to isolate and assess the effects of interest. Future studies could employ more ecologically valid settings to assess how mindfulness impacts perception of satiation and hunger signals in real consumption situations.

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Ethical statement

The studies presented in this paper were pre-approved by the Social Sciences Ethics Committee of Wageningen University & Research. A written consent was obtained from all participants at the beginning of each study.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2021.105280.

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