

High Hunger State Increases Olfactory Sensitivity to Neutral but Not Food Odors

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Abstract

Understanding how hunger state relates to olfactory sensitivity has become more urgent due to their possible role in obesity. In 2 studies (within-subjects: $n = 24$, between-subjects: $n = 40$), participants were provided with lunch before (satiated state) or after (nonsatiated state) testing and completed a standardized olfactory threshold test to a neutral odor (Experiments 1 and 2) and discrimination test to a food odor (Experiment 2). Experiment 1 revealed that olfactory sensitivity was greater in the nonsatiated versus satiated state, with additionally increased sensitivity for the low body mass index (BMI) compared with high BMI group. Experiment 2 replicated this effect for neutral odors, but in the case of food odors, those in a satiated state had greater acuity. Additionally, whereas the high BMI group had higher acuity to food odors in the satiated versus nonsatiated state, no such differences were found for the low BMI group. The research here is the first to demonstrate how olfactory acuity changes as a function of hunger state and relatedness of odor to food and that BMI can predict differences in olfactory sensitivity.

Key words: BMI, obesity, odor, olfaction, sensitivity

Introduction

The relationship between hunger state and olfactory sensitivity is important for both olfactory and appetite research. This connection has a more urgent need due to the obesity epidemic and the demonstration that obese adults have reduced olfactory sensitivity (Richardson et al. 2004).

Because the vast majority of what we attribute to taste does in fact come from our sense of smell, it could be that impaired olfactory sensitivity somehow interferes with mechanisms that signal satiation. Intuitively, we might think our ability to detect odors (especially food odors) would be enhanced in periods of high versus low hunger states, and indeed, these findings have been found in animal work for food-related (Apelbaum et al. 2005) and interestingly non-food-related (Aime et al. 2007) odors. This evidence supports the view of the close relation between the olfactory system and the hypothalamic feeding centers (Aime et al. 2007).

In studies involving human subjects, the findings are rather more mixed. For instance, Schneider and Wolf (1955) reported that sensitivity to the odor of citral (used in lemon flavoring) was higher before rather than following a meal,

which was also found for the odor of coffee by some researchers (Hammer 1951; Guild 1956) but not others (Janowitz and Grossman 1949; Zilstorff-Pedersen 1955). Work has also found the opposite effect, with higher sensitivity for phenylethyl alcohol (a nonfood odor) after food intake than before (Fikentscher et al. 1977). A later study argued that methodological differences may have explained these discrepant findings (Koelega 1994), also acknowledging a number of limitations to his own study including the fact that subjects chose their own lunch which may have led to different levels of satiation in addition to mood, both of which can influence olfaction (see Pollatos et al. 2007). Additionally, since that study, more standardized paradigms have been developed to test olfactory sensitivity, for example, the “Sniffin Sticks” test battery (Burghart Instruments) comprising 3 olfactory tests (threshold, discrimination, and identification). The threshold test uses pen-like instruments to determine the minimum concentration of an odorant that can be smelled by an individual and has been used extensively in research (Hummelet al. 2007; Albrecht et al.

2008). Using the Sniffin Sticks threshold test, recent research found no differences in sensitivity to nonfood odors (*n*-butanol, alcohol) in individuals tested before and after breakfast (Albrecht et al. 2009), though surprisingly, sensitivity was higher for a food-related odor (isoamyl acetate, banana) when tested after compared with before breakfast. This suggested that sensitivity to nonfood odors does not vary as a function of hunger state, but for food odors that sensitivity is actually higher in a low versus high hunger state. Though this study has extended research using a more standardized olfactory test and exerted more control over participants' food intake, there remains further unresolved questions. First, the same participants completed the olfactory tests twice in a relatively short space of time and hence there is a question as to practice/fatigue effects. Connected to this, because all the participants completed the tests in the same order (before and after breakfast), there remains the possibility of an effect of order. Second, it is possible that different findings might be seen when tested at lunch time rather than at breakfast (Koelega 1994). Third, because research has shown the influence of mood and personality on sensitivity (Chen and Dalton 2005; Pollatos et al. 2007), it would also appear important to take account of these factors. Finally, the previous study did not look at differences in odor discrimination between hunger states, so it is therefore uncertain whether in hunger state research, this test might be more sensitive in detecting an effect compared with the threshold test; hence, it therefore seemed important to include both tests.

The present study therefore aimed to examine further if olfactory acuity (threshold and discrimination) varied in different states of hunger. The study also aimed to explore further whether body mass index (BMI) could influence olfactory sensitivity and whether this was modulated by hunger state. Surprisingly, relatively few studies have examined differences of olfaction as a function of BMI and we are not aware of any work that has also investigated hunger state. One study did find that olfactory dysfunction was more common in morbidly (BMI > 45) compared with moderately (BMI < 45) obese individuals (Richardson et al. 2004), suggesting a possible link between poor sense of smell and overeating. However, in contrast, a larger sample (and lower BMI: 16–44), odor identification was higher in those individuals who had gained weight compared with those that had lost (Aschenbrenner et al. 2008). It therefore appears that the relationship between weight or BMI and olfactory acuity is not straightforward.

It was therefore tentatively predicted that olfactory sensitivity would be lower for those who were provided with lunch before (satiated) testing and thus in a low hunger state compared with those who were given lunch after (nonsatiated) testing and thus in a high hunger state. We further predict on the basis of previous work (Richardson et al. 2004) that olfactory sensitivity will be lower for those individuals with high compared with low BMI.

Study 1

Materials and methods

Participants

Twenty-four staff and students (19 females and 5 males) from the University of Portsmouth participated in the study and were aged between 19 and 49 years ($M = 30.5$ years, standard error [SE] = 1.7 years). The study was advertised on the University's website as examining factors that influence our sense of smell, and participants were requested to email the researcher to express interest. Only nonsmokers were invited to participate in the study. The study protocol was given ethical approval from the Department Ethics Committee (British Psychology Society guidelines).

Design

The study used a within-subjects design where participants (Table 1) attended 2 separate sessions that differed only in whether they received lunch prior to testing (satiated) or after testing (nonsatiated), the order of which was counterbalanced. At each session, participants completed olfactory threshold and discrimination tests. The main dependent variables were their scores in the 2 olfactory tests.

Lunch. Participants were asked to choose between 2 sandwich options, either chicken and bacon (470 Kcal) or cheese and celery (480 Kcal) (Marks & Spencer). They were also given a packet of Hula Hoops cheese and onion crisps (129 Kcal) and a bowl of chocolate chip cookies (126 Kcal) (Sainsburys). In order to ensure the lunches were acceptable, a pilot study was completed where 6 participants (3 females and 3 males) were presented with a selection of sandwiches with different fillings and a variety of sweet and savory snacks. The savory and sweet snacks with the highest pleasantness ratings were selected for the study. For the sandwiches, in order to cater for vegetarian and meat options, the 2 sandwiches with the highest pleasantness ratings that were also most similar on this dimension were selected.

Table 1 Mean (standard error) participant characteristics dependent on test order (Experiment 1, $N = 24$)

	Test order		Group differences
	Satiated/nonsatiated	Nonsatiated/satiated	
Age	30.6 (2.6)	30.5 (2.3)	$t_{22} = 0.45$, NS
BMI	23.5 (0.9)	22.9 (0.9)	$t_{22} = 0.42$, NS
Extraversion	40.4 (2.6)	38.5 (2.5)	$t_{22} = 0.53$, NS
Neuroticism	29.7 (2.2)	30.7 (2.5)	$t_{22} = 0.82$, NS
Total calories consumed (Kcal)	628.7 (36.6)	663.8 (28.6)	$t_{22} = 0.74$, NS
Female/male	11/2	8/3	$\chi^2_1 = 0.51$, NS

Personality measures. The EPQ-BV (Sato 2005) was used as the main personality measure. The EPQ-BV consisted of 2 measures, one for extraversion and one for neuroticism. This 24-item (12 for extraversion and 12 neuroticism) questionnaire consisted of 5-point Likert scales with response options ranging from not at all (1), slightly (2), moderately (3), very much (4), to extremely (5).

Mood measures. The Positive and Negative Affect Schedule (PANAS) from (Watson et al. 1988) was used to measure mood during the experiment. The PANAS consisted of 5-point Likert scales ranging from 1 (very slightly or not at all) to 5 (extremely) on which participants rated their feelings and indicated the extent to which they currently experienced 10 positive emotions (interested, excited, strong, enthusiastic, proud, alert, inspired, determined, attentive, and active) and 10 negative emotions (distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, and afraid).

Hunger and alertness ratings. Ratings of hunger were made using 100 mm unmarked line scales end-anchored “not at all” and “extremely,” with the adjective “hungry” centered above the line. In addition to this adjective, other mood adjectives were also used (alert and drowsy), mainly to divert attention away from the real purpose of the study but also to provide data on how temporary suspension of lunch might affect behavior.

Olfactory threshold and discrimination tests. The odor threshold and discrimination tests were from the Sniffin Sticks battery (Burghart Instruments) and were tested in a counterbalanced order. The pens for the threshold test contained 16 concentrations (strongest (1) = 4% down to weakest (16) = 1.22 ppm) of *n*-butanol (diluted by aqua conservans) and participants were presented with three sticks sequentially, 2 of which were blanks (aqua conservans only) and the third was the target odor. Testing commenced by asking participants to smell the pen with the highest concentration (amount) to familiarize themselves with the target odor. They were then presented with the triplet containing the weakest concentration. Following presentation of the last pen of the triplet (counterbalanced), participants were asked which pen contained the odor (1, 2, or 3). If the participant answered correctly (and it was the lowest concentration), they were presented with the same triplet again (in a different order) and the task repeated until they made a mistake, which resulted in the triplet containing the next concentration step being presented. Using a single up-down staircase system, this was then repeated until there were 7 “turning points,” with the mean of the last 4 points determining the threshold for the individual. Each odor “pen” was held under the participant’s nose (≈ 2 cm) and gently waved between each nostril to ensure optimal inhalation. The experimenter wore cotton gloves (Boots, Portsmouth) to reduce any cross contamination of odors.

In the discrimination task, 16 triplets of sticks were presented in a counterbalanced order, with 2 containing the same odor and the third a different odor. Subjects were asked to determine which one of the 3 odor-containing sticks differed in smell. Resulting scores ranged from 0 (none correct) to 16 (perfect discrimination).

Procedure

Participants were instructed not to eat anything after 11 PM the night before testing, consuming only water, tea/coffee, fruit juice. All testing commenced between 12 and 2 PM, with the additional proviso that participants attended both sessions at the same time, separated by at least 1 week. At the first session, participant’s height and weight were measured to calculate their BMI. Next, they completed baseline ratings of hunger and alertness, followed by mood (PANAS), and personality (EPQ-BV) questionnaires. Those in the lunch first condition were presented with their standard lunch and advised they had 20 min to eat as much as they could until they were full. Once this time had elapsed, participants were instructed to wash their hands (to avoid odors contaminating the olfactory tests) and taken to a large well ventilated room. Those that had just eaten lunch completed another hunger and general mood ratings form. They were then blindfolded with a black eye mask with a velcro strap (Boots) and completed the threshold and discrimination tests. Once this had finished, all participants completed final hunger and general mood ratings and PANAS questionnaire. At the end of the second session, they were given a full debriefing and paid 15 pounds for participation.

Data analyses

In both studies, data were analyzed using SPSS (version 16.0 for Windows, SPSS Inc.). The alpha levels for all tests were set at 0.05. Mauchly’s test was used to measure sphericity, and if sphericity was violated, Greenhouse–Geisser corrections were applied.

In order to examine the effect of BMI on olfactory sensitivity, participants were categorized as either low or high BMI by a median split; this resulted in 12 participants in the low and 12 in the high BMI group (there were no group differences in age or gender, both P s > 0.30). For the threshold data, 2 participants failed to reach a threshold score (i.e., successive failed attempts) on one of the test sessions, and therefore their data for this session were not included. The remaining data were subjected to a repeated-measures analysis of variance (ANOVA) using the within-subjects factor of Hunger state (satiated/nonsatiated) and the between-subjects factors of test order (satiated/nonsatiated, nonsatiated/satiated) and participant BMI (low/high). This method was replicated for the discrimination scores. Hunger ratings were analyzed using a repeated-measures ANOVA, using the within-subjects factor time (baseline, final) and the

between-subject factor of test order (satiated/nonsatiated, nonsatiated/satiated).

To explore the relationship between olfactory sensitivity and individual differences, bivariate correlations were completed with the threshold and discrimination scores in each condition (satiated/nonsatiated) and the data relevant for that day (mood, food intake) and extraversion/neuroticism scores.

Results

Hunger

For hunger ratings, there was an effect of hunger state, $F_{1,22} = 88.44$, $P < 0.001$, $\eta^2 = 0.80$, time, $F_{1,22} = 156.54$, $P < 0.001$, $\eta^2 = 0.88$, qualified by a hunger state \times time interaction, $F_{1,22} = 150.12$, $P < 0.001$, $\eta^2 = 0.87$, where ratings decreased for those satiated from baseline to end of study ($M = 73.1$, $SE = 4.4/M = 8.3$, $SE = 1.7$) but remained stable for the nonsatiated condition ($M = 74.4$, $SE = 4.4/M = 75.3$, $SE = 4.9$).

Odor threshold test

Analyses revealed there was no main effect of hunger state, $F_{1,18} = .74$, $P = 0.40$, $\eta^2 = 0.05$, which was against prediction. However, the hunger state \times test order interaction, $F_{1,18} = 4.48$, $P = 0.048$, $\eta^2 = 0.20$, demonstrated a general practice effect with both groups improving on the second session, irrespective of hunger state (Table 2). This being the case, to exclude any possible practice effect, the data were reanalyzed using only the first session (Day 1). This demonstrated a significant effect of hunger state, $F_{1,20} = 5.44$, $P = 0.03$, $\eta^2 = 0.21$, and consistent with prediction, higher sensitivity in the nonsatiated compared with satiated group (Figure 1). A main effect for BMI was also found, $F_{1,20} = 9.15$, $P = 0.007$, $\eta^2 = 0.31$, and in support of our hypothesis, higher sensitivity in the low ($M = 8.9$, $SE = 0.64$) versus high BMI group ($M = 6.2$, $SE = 0.65$). No effects were found for the discrimination test.

Correlations

Significant associations were found for the threshold data only, where for the satiated condition, this revealed an approaching negative correlation for drowsiness ratings (baseline), $r_{24} = -0.39$, $P = 0.061$ where increases in drowsiness were associated with decreases in olfactory sensitivity. For

Table 2 Mean (standard error) scores for odor threshold for *n*-butanol (neutral odor) dependent on hunger state and test order (Experiment 1, $N = 24$)

Test order	Hunger state	
	Satiated	Nonsatiated
Satiated/nonsatiated	6.5 (0.63)	7.9 (0.61)
Nonsatiated/satiated	9.1 (0.63)	8.6 (0.61)

the nonsatiated condition, sensitivity correlated inversely with baseline, $r_{22} = -0.40$, $P = 0.065$, and posttest negative (PANAS) ratings, $r_{22} = -0.44$, $P = 0.04$, suggesting that increases in negative mood impaired olfactory sensitivity.

Discussion

The main findings of the study were that consistent with prediction, olfactory sensitivity was greater in a high compared with low hunger state when the influence of practice effects had been excluded. Further that low versus high BMI individuals had higher olfactory sensitivity, which provide further support to previous research (Richardson et al. 2004). The finding of a general practice effect in the threshold task was interesting because this was not shown in a previous study (Albrecht et al. 2008) where threshold performance was repeated over 4 time intervals (0, 35, 105 min, and 35 days). The time of day participants were tested was not reported in that study, so it could be that this might exert some influence, together with the fact that an older sample was used here ($M = 30.5$ years) compared with the previous study ($M = 27.9$ years). The absence of an effect of hunger state on odor discrimination was perhaps surprising because odor discrimination correlates with cognitive processes (e.g., free recall, letter fluency) (Hedner et al. 2010), which in turn can be affected by hunger state (Hoyland et al. 2008). By extension, one might then expect for suspension of lunch to lead to lower levels of blood glucose and thereby impair odor discrimination as has been found in general memory (Benton et al. 1994). However, in contrast to the present lunch time study, most of these studies have been conducted in the

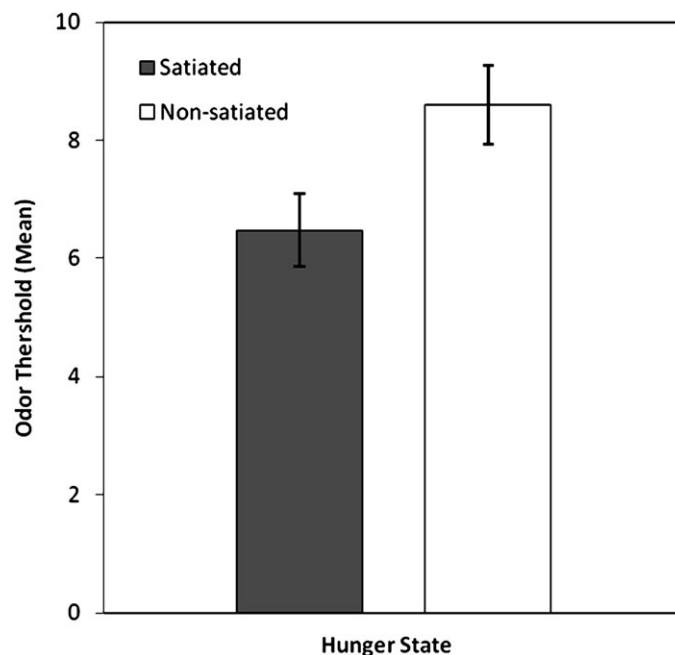


Figure 1 Mean (\pm standard error) olfactory threshold for *n*-butanol (neutral odor) depending on hunger state (Day 1 only, Experiment 1).

morning and as has been theorized elsewhere (Hoyland et al. 2008), circadian rhythms may well influence cognitive performance above and beyond meal manipulation.

The observed association between negative mood and olfactory threshold was interesting. This supports previous work where negative mood induction reduced olfactory sensitivity (Pollatos et al. 2007) and perhaps emphasizes the close relationship between olfaction and emotion (Herz and Engen 1996).

Although the current study did find evidence that olfactory sensitivity was affected by hunger state, a second experiment was required to see whether this effect could be replicated and given the observed practice effects, a between-subjects design appeared to be the most appropriate design. Because there were no effects in the Sniffin Sticks discrimination task, we tested only the threshold part of this test battery. Additionally, the previous study found that sensitivity to food-related odors was actually higher in a low compared with high hunger state (Albrecht et al. 2009). This was, however, based on an odor (banana) that participants also experienced during their breakfast (i.e., a banana was part of the meal) and hence it is unclear whether this may have had some influence on subsequent sensitivity. Experiment 2 aimed to see if this effect could be replicated. On the basis of the first experiment, we therefore predicted that sensitivity to the neutral odor would be higher in a nonsatiated compared with satiated state. In contrast, according to previous work (Albrecht et al. 2009), we hypothesize that sensitivity to a food odor would be higher in a satiated versus nonsatiated state.

Study 2

Materials and methods

Participants

Forty students (26 females and 14 males) from the University of Portsmouth participated in the study and were aged between 18 and 42 years ($M = 19.7$ years, $SE = 0.6$ years). They were recruited through an advertisement on the University's participant pool website which informed them that the study was investigating our ability to distinguish different types of odors. As in study 1, only nonsmokers were invited to participate in the study.

Design

The study used a between-subjects design where participants were randomly allocated to a satiated (S) or nonsatiated (NS) condition (Table 3), completing the neutral odor, then food odor tests in a fixed order. The main dependent variables were their scores in the 2 olfactory tests.

Olfactory threshold test—neutral odor. The same odor threshold (Sniffin Sticks) test was used as in Experiment 1.

Table 3 Mean (standard error) participant characteristics (Experiment 2, $N = 40$)

	Satiated	Nonsatiated	Group differences
Age	19.9 (1.2)	19.4 (0.3)	$t_{38} = 0.45$, NS
BMI	21.91 (0.9)	21.89 (0.6)	$t_{38} = 0.02$, NS
Female/male	17/3	11/9	$\chi^2_1 = 7.03$, $P < 0.01$

Olfactory discrimination test—food odor. A preliminary study was conducted to obtain the most appropriate concentrations of the food-based odorant that would be used in the main experiment. In order to use an odorant with high ecological validity and affinity to a range of food products, a food industry herb-based odorant was used (Herbs 85/18845 natural flavoring, House of Flavor). Four different amounts: 2.00, 5.00, 10, and 15 μL were poured into 4 separate 250-mL polypropylene squeeze bottles (CJK Packaging Ltd), equipped with a flip-up spout, with each bottle containing 50 mL mineral oil (Nujol, Fisher Scientific) as the diluting agent. This yielded 4 different concentrations: 0.004%, 0.01%, 0.02%, and 0.03%. During the preliminary study, participants (5 male and 5 female) were presented with the 4 odors in a counterbalanced order and for each odor were asked to rate the confidence with which they could detect any odor using a 5-point Likert scale (from “not at all difficult” to “extremely difficult”). To avoid evident ceiling effects for the main study, the concentration with the lowest scores in detection (0.004%) was used as the starting concentration for the main study, with each successive odorant increasing by 1 μL , producing 5 concentrations in all: 1) 0.004%, 2) 0.006%, 3) 0.008%, 4) 0.01%, and 5) 0.012% and a control stimulus was used which contained only mineral oil. For the main study, a triangle test was used to test olfactory discrimination to these 6 odors, where participants were always presented with 3 bottles (2 of which were always the same odor) and had to decide which odor was different. In total, there were 30 trials. The main measure in this test was the number of correct discriminations for each of the concentrations.

Procedure

The same protocol was followed as per Experiment 1. The main difference was that following the completion of the threshold test, participants were asked to remove their eye mask and given a short break (≈ 5 min) before commencing the food odor discrimination test. Once this had finished, participants completed a final hunger and general mood ratings questionnaire and were then given a full debriefing.

Data analyses

For the threshold data, one participant failed to reach a threshold score and therefore their data were excluded. As with the previous study, to examine the influence of

BMI, participants were categorized as either low or high BMI by a median split; this resulted in 21 low and 18 high BMI (there were no group differences in age or gender, both P s > 0.30). The threshold data were analyzed using an independent t -test with hunger state (satiated/nonsatiated) as the between-subjects factor. The discrimination data were analyzed using a repeated-measures ANOVA using the within-subjects factor of concentration (1–5) and the between-subjects factor was hunger state (satiated/nonsatiated). Ratings of hunger were analyzed using a repeated-measures ANOVA, where ratings were entered as the dependent variable; the within-subjects factor was time (baseline, final), whereas the between-subject factor of hunger state (satiated/nonsatiated). Bivariate correlations were used to explore the relationship between overall mood, hunger, and olfactory sensitivity to neutral and food odors.

Results

Hunger

We found main effects of time, $F_{1,37} = 46.30$, $P < 0.001$, $\eta^2 = 0.56$, lunch, $F_{1,37} = 33.62$, $P < 0.001$, $\eta^2 = 0.48$, which were qualified by a hunger state \times time interaction, $F_{1,37} = 20.44$, $P < 0.001$, $\eta^2 = 0.36$, with hunger ratings decreasing more acutely in the satiated ($M = 70.1$, $SE = 3.4/M = 25.9$, $SE = 5.4$) versus nonsatiated ($M = 82.2$, $SE = 3.5/M = 73.1$, $SE = 5.5$).

Neutral odor threshold test

Analysis revealed a significant effect of hunger state, $F_{1,35} = 3.95$, $P = 0.027$ (one-tailed), $\eta^2 = 0.10$, with as predicted higher threshold scores in the nonsatiated compared with satiated group (Figure 2). There were no effects of BMI or hunger state \times BMI interaction (both F s < 1). Because there was no effect of BMI together with the fact that the observed hunger state effect was somewhat smaller than study 1, we also analyzed the combined threshold data of both studies. This demonstrated a larger effect of hunger state, $F_{1,59} = 8.28$, $P = 0.006$, $\eta^2 = 0.12$, with as expected higher threshold in the nonsatiated ($M = 8.8$, $SE = 0.43$) versus satiated ($M = 7.1$, $SE = 0.41$) group and an approaching effect of BMI, $F_{1,59} = 3.38$, $P = 0.07$, $\eta^2 = 0.05$, and consistent with study 1, greater sensitivity in the low BMI ($M = 8.5$, $SE = 0.42$) compared with high BMI ($M = 7.4$, $SE = 0.42$) group.

Food odor discrimination test

An effect of concentration was found, $F_{4,140} = 22.84$, $P < 0.001$, $\eta^2 = 0.40$, with accuracy increasing with each level of concentration (Table 4). More importantly, consistent with prediction, there was an effect of hunger state, $F_{1,35} = 11.62$, $P = 0.002$, $\eta^2 = 0.25$, where overall discrimination was higher in the satiated ($M = 2.83$, $SE = 0.13$) compared with nonsatiated state ($M = 2.28$, $SE = 0.13$), suggesting that sensitivity to food odors was higher in a low

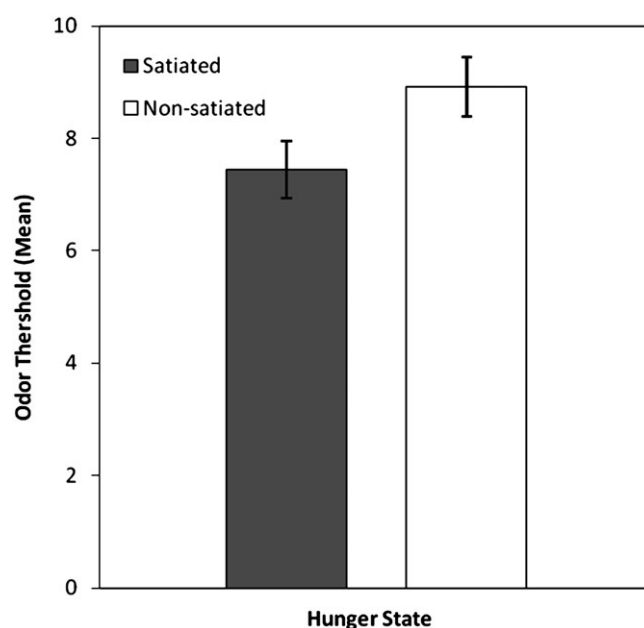


Figure 2 Mean (\pm standard error) olfactory threshold for *n*-butanol (neutral odor) depending on hunger state (Experiment 2).

Table 4 Mean (standard error) scores for food odor discrimination tests dependent on hunger state and odor concentration (Experiment 2, $N = 39$)

Odor concentration (%)	Satiated	Nonsatiated	Group differences (P value ^a)
0.004	0.85 (0.25)	0.89 (0.26)	0.96, NS
0.006	3.00 (0.28)	1.53 (0.29)	0.001
0.008	3.45 (0.28)	2.89 (0.29)	0.15, NS
0.01	3.30 (0.34)	3.21 (0.34)	0.69, NS
0.012	3.55 (0.33)	2.89 (0.34)	0.48, NS

^aBonferroni adjustment for multiple comparisons applied

versus high hunger state. The effect of BMI approached significance, $F_{1,35} = 3.06$, $P = 0.09$, $\eta^2 = 0.08$, qualified by a significant hunger state \times BMI interaction, $F_{1,35} = 4.81$, $P = 0.04$, $\eta^2 = 0.12$, where in the satiated state, discrimination was greater for the high versus low BMI group ($P < 0.01$), with no equivalent differences in the nonsatiated ($P = 0.76$) state (Figure 3).

Correlations

Significant correlations were found between food odor discrimination and baseline, $r_{39} = 0.52$, $P = 0.001$, and final alertness ratings, $r_{39} = 0.47$, $P = 0.003$, suggesting that across lunch conditions, increases in alertness were associated with increasing olfactory performance to food odors. More interestingly, final hunger ratings correlated with both food, $r_{39} = -0.35$, $P = 0.03$, and neutral, $r_{39} = 0.36$, $P = 0.02$, odor tests but in different directions; where increases in hunger were associated with decline in food but increase in neutral odor performance.

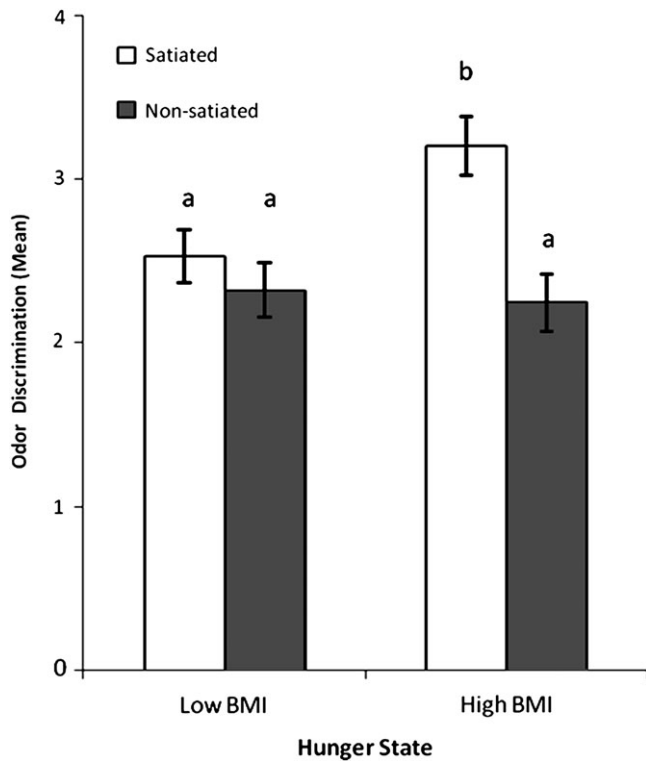


Figure 3 Mean (\pm standard error) olfactory discrimination (food odor) depending on hunger state and BMI (Experiment 2). Note: means denoted by different letters are significantly different: $P < 0.01$.

Discussion

The study found that olfactory sensitivity to neutral odors was significantly higher in a high versus low hunger state, which is consistent with the prediction and Experiment 1. Though, in Experiment 1, this could only be claimed for part of the data (Day 1) due to the practice effect in the threshold test. The replication of this finding in the present experiment provide firmer support for the theory that humans have heightened olfactory detection to nonfood odors in periods of hunger compared with satiation and agree with some early work in this area (Hammer 1951; Guild 1956) but not with the most recent work (Albrecht et al. 2009), which is interesting given that both used the same method of measuring olfactory threshold. However, there are a number of differences between the 2 studies that may well help unravel the contrasting findings, with possibly the key difference being the differences in design. Experiment 1 used the same within-subjects design as that work (Albrecht et al. 2009) and also failed to detect differences between hunger states but did find an effect when looking at Day 1 only (effectively making it a between-subjects design). This was further confirmed in a between-subjects experiment here, which all make it seem likely that design is of central importance in detecting any effects to neutral odors in hunger state research, although we recognize that practice effects were not seen in other previous work (Albrecht et al. 2008). Additionally,

both experiments here tested individuals at lunch time rather than in the morning (Albrecht et al. 2009), suggesting this might also be relevant. Specifically, we requested participants to fast from 11 PM the evening before testing which equates to around 13 h fasting compared with 10 h in the previous study (Albrecht et al. 2009). Examination of the hunger ratings (when converted to the same scale) also demonstrate individuals in the experiments here were more hungry at the start of their session compared with the previous study. It may be therefore that the magnitude of hunger also has some influence on sensitivity to neutral odors, which is also supported by our finding of a positive association between hunger ratings and neutral odor sensitivity.

The finding that sensitivity to food odors was actually higher in a low compared with high hunger state is congruent with the previous study (Albrecht et al. 2009), and in contrast to neutral odors suggest that being in a satiated state enhances olfactory sensitivity. One of the limitations acknowledged by those authors was that the food odor used in their study was the same as one of the food items in the breakfast itself (isoamyl acetate, banana) and hence the observed higher sensitivity could have been due to a priming effect of having just experienced the same odor. In the present experiment, by using a between-subjects design and a food odor unrelated to the meal itself, we can be more confident of this effect which further inform research in this area. Hence, following a satiating meal, olfactory acuity for food-related odors increases, whether or not they are associated to the meal just consumed.

To understand the magnitude of the change in olfactory sensitivity due to hunger state, the effect sizes were compared against Cohen's values (Cohen 1988) and correspond to a large effect for the neutral odor (using Cohen's tables for ANOVA, mean of study 1 [$\eta^2 = 0.21$, very large effect] + Study 2 [$\eta^2 = 0.10$, medium/large effect] = 0.16 [large effect, equivalent to Effect Size_{It} = 0.80]) and a large to very large effect for the food (Study 2 [$\eta^2 = 0.19$ = large/very large effect]) odor. These effects are, however, rather modest compared with differences in clinical populations, for instance, between normosmia and hyposmia populations (Aschenbrenner et al. 2008), the effect size is double the magnitude as those found here (from the data provided, we calculate an effect size for threshold scores of $d = 1.8$). Nevertheless, a closer comparison would be to different age populations (Hummel et al. 2007), where looking at olfactory sensitivity between young (16–35 years) and old (55 years+) groups (taking the data from that study, we calculate an effect size for threshold scores of $d = 0.64$), one could say that the effect sizes in both neutral and food odors in the present study are roughly equal to the difference between these 2 age groups. To put this into perspective, on average, the drop in olfactory function between these 2 groups is around 25%, which is similar to the changes seen in both neutral and food odor as a consequence of hunger state. In summary, although the magnitude does not reach clinical levels, when we consider

the general lifestyle changes that separate the 2 age groups used for comparison (Mitchell et al. 2000), the observed differences in olfactory sensitivity are nevertheless important.

General discussion

The findings from the studies here build on and extend previous research in a number of different ways. Experiment 1 found that sensitivity to a neutral odor was higher in a high compared with low hunger state. This basic effect was replicated and extended in Experiment 2 by the observed interaction of hunger state and odor (neutral/food) test, providing a unique insight into this phenomenon, suggesting that hunger state can predict olfactory acuity, but this is qualified by whether or not the odor is related to food. At first glance, this seems counter intuitive because on the basis of evolutionary theory, we might well expect the ability to detect foods that are edible and ripe to be more advantageous in a hungry compared with satiated state. Though it could be theorized that better olfactory acuity following a meal might in fact aid in the regulation of food intake, that is, as it is then easier to detect and reject foods that are no longer required. This point was also raised previously (Albrecht et al. 2009) and supported by their evidence of lower pleasantness ratings of the food odor in a satiated versus hungry state, with no corresponding change in the nonfood odor. To an extent, this agrees with our finding of decreases in hunger predicting higher sensitivity to food odors; thus, detection of food odors is increased for individuals in a lower state of hunger. Theoretically speaking, the findings in the present research connect together work showing decreases in hedonic (pleasantness) ratings of food odors depending on hunger state and the sensitivity to food odors in different states of hunger. On the one hand, it has been demonstrated that odors of foods consumed to satiety undergo a fall in hedonic ratings, which are not seen in odors of nonconsumed foods (Rolls ET and Rolls JH 1997) also that acquired liking of a novel food odor can be reversed if preceded by a high versus low energy meal (Yeomans and Mobini 2006). We also now know that following satiation, sensitivity to food odors increases irrespective of their connection to the food just consumed. Extrapolating these findings, we might predict in the study here that pleasantness ratings of the food odor would not have decreased based on earlier work (Rolls ET and Rolls JH 1997) and therefore that changes in hedonic ratings are not responsible for alterations in sensitivity to food odors; though future research that included pleasantness ratings would need to confirm this theory.

The finding of higher sensitivity to neutral odors in a high hunger state is supported by previous research for the odor of coffee (Hammer 1951; Guild 1956), which although having some association with food (e.g., coffee and cake/other sweet products, Stafford et al. 2009), is not strictly a food odor and therefore to some extent agree with the findings here. In order to explain these effects, researchers have tended to follow the theory that increased olfactory sensitiv-

ity in times of hunger aids in locating food (Koelega 1994), which at face value does not seem plausible for a clearly non-food odor such as *n*-butanol. However, the finding that rats are also more sensitive to neutral odors in a high versus low hunger state (Aime et al. 2007) was theorized to facilitate increased detection of predators during food foraging. In humans, it could be that having a higher olfactory sensitivity in such times may not directly aid in food “odor” detection, but in some other activity (connected or not with food procurement), for example, detecting pheromones in potential mates, detecting kin from nonkin, and detecting disease in kin (Brown 1995; Thornhill and Gangestad 1999), many of which help group fitness in hunting/searching for food.

The finding that olfactory sensitivity also differed in terms of BMI is a further novel finding. Study 1 found that individuals with a high compared with low BMI had poorer sensitivity to the neutral odor, a trend also found when the data from both studies were combined. Previous work has demonstrated that obesity relates to olfactory dysfunction (Richardson et al. 2004) and lower sensitivity to the odor of coffee (Guild 1956), both of which agree with our neutral odor findings here. In contrast, it has been found that taste sensitivity for sucrose and salt to be higher in massively obese compared with nonobese adolescents (Pasquet et al. 2007), which are consistent with the present findings of greater acuity for food odors in the high compared with low BMI group. So it could be that perception of food but not nonfood-related tastants/odors is higher in obese individuals. More specifically, the current study found that the food odor effects were most clearly observed in the satiated condition, suggesting that hunger state is important in detecting any food odor-related differences in BMI. Interestingly, this could be taken as evidence that because these individuals are higher in BMI that having higher acuity for food-related odors just following a meal may not actually aid in the control of food intake but rather help sustain food intake. Though we recognize that olfactory and taste sensitivity are only one factor in a complex chain that influence weight gain and obesity (Donaldson et al. 2009).

Differences in olfactory acuity are a promising new area of obesity research. Nevertheless, as has been commented elsewhere (Richardson et al. 2004), it is unclear whether differences in olfactory function are a cause or consequence of obesity. One could infer that the former is unlikely because research has shown that in a sample of individuals with congenital anosmia, the frequency of those who were overweight was no higher than in the general population (Aschenbrenner et al. 2008). Hence, if olfactory dysfunction is a main driver in obesity, we might have expected a higher occurrence of obesity in these anosmics.

In terms of limitations of the work here because we did not control for odor presentation order (Experiment 2), there remains the possibility of an order effect. The rationale for using a fixed order was to avoid any possible contamination of food odor on the neutral odor threshold test and also the

possibility that the inhalation of a food odor might induce a feeling of satiation (Rolls ET and Rolls JH 1997) and thus compromise the manipulation for those individuals in the nonsatiated condition. One alternative to avoid this problem for future work would be to use separate groups for the food and nonfood odors. Another limitation concerns the food odor test itself which although including different concentrations of the odor was more a test of odor discrimination rather than absolute threshold; the latter being used in the earlier study (Albrecht et al. 2009) and therefore limits direct comparison with that work. Future research should utilize both discrimination and threshold tests for each neutral and food odorants. Additionally, in both studies, prior to testing, participants were instructed to consume only water, tea/coffee, and fruit juice; however, because some fruit juices can be highly calorific, future research should exclude such beverages. Note, however, that tea/coffee is important to include, in order to avoid any negative withdrawal symptoms that might be experienced (Stafford and Yeomans 2005), which may cause discomfort and indirectly affect olfactory acuity. Lastly, because there was a difference in the number of males/females in each group for Study 2, one could argue that since some work has shown that females have higher olfactory acuity (Hummel et al. 2007) that this might explain some of these effects, particularly in the food odor test, where there were a higher proportion of males in the nonsatiated group. Hence, it could be contended that this group had lower discrimination not because of their hunger state but rather their higher number of males. To check if this might be the case, we completed an additional test of this group, which found no sex differences in either the neutral or food odor tests (both $P_s > 0.20$). Nevertheless, for completeness, future research should attempt to balance between sexes.

In conclusion, the research here has helped clarify previous contradictory findings on the relationship between hunger state and olfactory sensitivity by demonstrating the dependence on the odor itself; acuity to a neutral odor was greater in a high hunger state with the reverse being true for a food-related odor. Furthermore, individuals high in BMI were found to have higher acuity to food but not neutral-related odors compared with those low in BMI, with the provision of lunch (and thus in a low hunger state) acting to increase sensitivity to food odors for high but not low BMI individuals.

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