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Chemosensory abilities in consumers of a Western-style diet

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Abstract

People vary in their habitual diet and also in their chemosensory abilities. In this study we examined whether consumption of a Western-style diet, rich in saturated fat and added sugar, is associated with either poorer or different patterns of chemosensory perception, relative to people who consume a healthier diet. Participants were selected based on a food frequency questionnaire, which established whether they were likely to consume a diet either higher or lower in saturated fat and added sugar. Eighty-seven participants were tested for olfactory ability (threshold, discrimination, identification), gustatory ability (PROP sensitivity, taste intensity, quality and hedonics), and flavour processing (using dairy fat-sugar-odour mixtures). A Western-style diet was associated with poorer odour identification ability, greater PROP sensitivity, poorer fat discrimination, different patterns of sweetness taste enhancement, and hedonic differences in taste and flavour perception. No differences were evident for odour discrimination or threshold, in perception of taste intensity/quality (excluding PROP) or the ability of fats to affect flavour perception. The significant relationships were of small to moderate effect size, and would be expected to work against consuming a healthier diet. The discussion focuses on whether these diet-related differences precede adoption of a Western-style diet and/or are a consequence of it.

Keywords: Olfaction, Gustation, Flavour, Diet, Food choice

Introduction

Although people change what they eat, the idea that they can maintain broadly stable patterns of food intake over the long term (e.g., years to decades) has been confirmed in several studies (e.g., Pachuki, 2012; Newby, 2006). Routinely eating diets rich in saturated fat, and added sugar - a Western-style diet - in contrast to a plant-based diet, is associated with poorer health outcomes (e.g., Appel et al., 1996; Mente et al., 2009). This makes it important to study the drivers of dietary choice. While many factors impact dietary choice (e.g., education, poverty, impulsivity), one potentially important factor is chemosensory ability. This is relatively unexplored, with most focus to date on alcohol consumption (e.g., Bachmanov, 2003) and on genetically based sensitivity to bitter tasting propylthiouracil (PROP; Duffy et al., 2009; Feeney, 2011; Hayes et al., 2010; Hayes et al., 2013). Far less attention has been paid to how variation in olfactory abilities, taste perception beyond PROP sensitivity, and the integration of taste, olfaction and somatosensation into flavour, may relate to diet. Here, we examine whether and how variation in chemosensory ability, for olfaction, taste (including PROP) and flavour, is linked to consumption of a Western-style diet.

Dietary preferences may be influenced by pre-existing perceptual differences. In the context of a Western-style diet, we hypothesise that one such difference may be a poorer sense of smell. If a person's olfactory ability is poor, this may be compensated for by choosing foods that involve greater stimulation of the taste and oral somatosensory systems (i.e., irritant and fat perception). While there is no direct data as yet regarding habitual diet and olfactory ability in general populations, there is circumstantial evidence favouring a link. One line of evidence comes from data we have collected. Some participants who had completed the Sniffin sticks (Hummel et al., 1997) odour discrimination and identification tests as part of one study in our laboratory, also provided dietary data as part of another. There were significant associations between their olfactory ability and reported diet, with a Western-style diet associated with poorer discrimination ($n = 86$; $r = -0.25$) and identification ($n = 86$; $r = -0.22$).

There are two further reasons to think that poorer olfactory ability may be associated with an inferior diet. First, obese individuals show preferences for sweeter (e.g., Drewnowski et al., 1985) and especially fattier (Cox et al., 2016) stimuli, and some studies find olfactory impairments among the obese (e.g., Richardson et al., 2004; but see Stafford & Whittle, 2015). Olfactory impairments could of course be caused by obesity, rather than predating it, but these findings are at least consistent with the view that poorer olfaction might result in weight gain. Second, people with an impaired sense of smell, including the elderly (Duffy & Hayes, 2014), often report dietary alterations. These may include adding more sugar, increasing spice use, and reducing plant-based foods (Merkonidis et al., 2015; Miwa et al., 2001; Van Toller, 1999) - although the impact of impaired olfaction on body weight is variable (e.g., Ferris & Duffy, 1989). Here, we tested whether performance on standardised tests of olfaction (Sniffin Sticks; Hummel et al., 1997) would be poorer in consumers of a Western-style diet.

We also examined whether a Western-style diet would be related to variation in taste perception. Two hypotheses can be advanced here. First, as a Western-style diet involves more processed food, and less fruit and vegetables, this would suggest the possibility of greater sensitivity to bitter tasting PROP. This is premised upon the association between sensitivity to genetically determined bitter taste perception ability and dietary preferences for cruciferous vegetables (Feeney, 2011; Hayes et al., 2013). Second, as processed foods contain higher levels of sugar, salt and fat than non-processed food, exposure to them might increase preference for more concentrated forms of these tastants (with fat mentioned here simply as it seems to be perceived via multiple sensory channels; Frost & Janhoj, 2007). In contrast, reduced intake of fruits and vegetables, might be associated with reduced exposure to sour and bitter tastes, and hence (e.g., via mere exposure) reduced preference for such tastants. That dietary exposure can selectively affect taste preference has been shown in several studies (e.g., Bertino et al 1982; Bertino et al., 1986) and in naturalistic studies of populations who consume different diets (e.g., bitterness/sourness; Moskowitz et al., 1975). While preference changes

seem well supported taste intensity perception appears to be stable and largely independent of dietary exposure (e.g., Cicerale et al., 2012; Mattes, 1985; Moskowitz et al., 1975), thus no relationship with habitual diet would be expected here.

A third set of predictions relate to flavour. Flavour perception, in the context of this study, has two main attributes. The first concerns sensory interactions in the mouth. These come in two forms: (1) the ability of certain tastants and odourants to affect odour and taste quality perception such that sweet tastants can enhance the intensity of previously co-experienced odours (e.g., Von Sydow et al., 1974), and that previously co-experienced odours can enhance the intensity of sweet tastants (e.g., Frank & Byram, 1988); and (2) the ability of fats to suppress the intensity of odourants. Both of these effects have a well-established psychological basis (Bult, de Wijk & Hummel, 2007; Sakai et al., 2001) and both could either be influenced by or influence habitual diet (e.g., poorer odour-taste integration resulting in less sweetness taste enhancement could be associated with a preference for more added sugar). Several possible effects are plausible, but the absence of any prior data precludes direction-specific predictions. The second main flavour attribute is hedonics (Stevenson, 2009). Not only may liking for different flavour combinations differ depending upon prior dietary exposure but capacity to integrate the sensory dimensions of flavour could also affect liking.

To examine whether participants who differ in adherence to a Western-style diet also differ in their olfactory, taste and flavour perception abilities, we recruited people differing on this dietary dimension. Western-style dietary intake was established using a reliable and validated brief food frequency scale (Dietary Fat and Sugar questionnaire; DFS; Francis & Stevenson, 2013). While we used standardised tests for olfactory ability and PROP taste intensity – as these are well established commercially (for Sniffin sticks) and in the literature (for both; e.g., Hummel et al., 1997; Kirkmeyer & Tepper, 2005; Prescott, Ripandelli & Wakeling, 2001), we employed bespoke tests to examine taste and flavour perception. For taste, participants evaluated sweet and salty tastes at two superthreshold concentrations, along

with the PROP sample and a sour taste. For flavour, we loosely modelled our design on the Drewnowski et al., (1985) approach, providing participants with dairy samples that varied in fat, sugar and fruit odourant concentration. For both the tastes and flavour samples, participants evaluated their intensity, qualities and hedonics using labelled magnitude scales (Green et al., 1996; Lim, Wood & Green, 2009). Finally, we collected basic demographic, medical chemosensory information and body mass index (BMI), to check that these variables were not responsible for any observed dietary associates of chemosensory ability.

Method

Participants

Participants were recruited in two ways. The first involved asking people who had completed an earlier study looking at the relationship between diet and memory if they wished to take part in a further (i.e., this) study. Originally, all participants in the earlier study had completed the Dietary Fat and Sugar questionnaire (DFS; Francis & Stevenson, 2013) as part of a screening program to identify individuals who differed maximally in saturated fat and added sugar intake, so as to ensure a wide spread of DFS scores. Participants who had a DFS score above 70 or below 55 (scores on the DFS can range from 26 to 130), who reported a BMI between 17 and 26 (broader because this was a self-estimate and included people of both Caucasian and Asian descent), were aged between 17 and 35, who had consented to be approached, and passed the medical screening (described below), formed the pool from which the earlier diet and memory study were recruited – and from which 60 people here were recruited.

The second recruitment method drew upon the university community. Using advertisements posted around campus, interested parties were invited to phone the study team about participation. On phoning they were asked about their frequency of consumption for the seven items from the DFS that have the highest item-total correlations (Soft drinks; Cakes &

Cookies; Pizza; Fried chicken, or chicken burgers; Doughnuts, pastries, croissants; Corn chips, potato chips, popcorn with butter; French fries, fried potatoes). Participants aged 17-35, with a BMI between 17-26, and who scored below 16 or above 21 on this short-form of the DFS were potentially eligible to take part. Potential participants also received a medical screening interview, which was also successfully completed by participants in our earlier diet and memory study. This assessed current (physical or mental illness; chronic conditions; recent hospitalisations; any history of eating disorders; any head injuries; food allergies), and past health issues. Participants who reported anything other than minor health complaints were excluded. Using this advertisement route, 28 participants were recruited.

Eligible participants were instructed to breakfast or lunch as per normal, but to refrain from eating (and smoking if they were a smoker) in the 2 hours before testing. Participants were also told that they could drink water in this period but not caloric beverages and not to exercise beyond their normal pattern.

In total 88 participants completed the study. Data from one participant was excluded as they were unable to breathe properly due to nasal congestion during testing. The same pattern of significant findings obtains when this participant's available data are included.

Materials

Olfactory testing: This was undertaken using the Sniffin-sticks test battery (Hummel et al., 1997), which involves a 16-item odour identification test, a 16-item odour triad discrimination test, and a butanol odour threshold test (Burghart Medizintechnik, Germany).

Gustatory testing; Seven test solutions were prepared: 0.17M ('strong salt') and 0.03M ('weak salt') saline solutions, plus a 0.1M saline standard; 0.36M ('strong sugar') and 0.03M ('weak sugar') sucrose solutions; a 0.04M citric acid (Sigma-Aldrich, Sydney, Australia) solution; and a 0.32mM PROP (Sigma-Aldrich, Sydney, Australia) solution - this concentration and that of the preceding saline standard were based upon prior studies (Prescott,

178 Ripandelli & Wakeling, 2001; Kirkmeyer & Tepper, 2005). 10ml of each tastant were
179 presented in disposable 30ml sample cups.

180 Flavour testing: Factorial combinations of three components were used to make the 18
181 samples used for flavour testing. These components were full cream milk (3.4% fat, 3.4%
182 protein, 4.9% carbohydrates) and skimmed milk (0.1% fat, 3.4% protein, 4.9% carbohydrates),
183 three levels of added sucrose, and three levels of added cherry odourant (Givaudan). The final
184 percentages of fat, added sucrose (noting that both milks contain the same base level of
185 naturally occurring sugars) and cherry flavourant for the samples were: (1) all 9 skimmed milk
186 samples contained 0.08% fat, and all 9 full fat milk samples contained 2.8% fat; (2) the 6
187 samples with lowest level of added sugar contained 0.5% w/v (0.015M), the 6 samples with an
188 intermediate level of added sugar contained 3.8% w/v (0.11M), and the 6 samples with the
189 highest level of added sugar contained 11.7% w/v (0.34M); and (3) for the cherry odourant, 6
190 samples contained no cherry odourant, 6 contained $1.3x10^{-4}$% w/v, and 6 contained $4.2x10^{-4}$%
191 w/v. All samples were of 10ml presented in disposable 30ml sample cups.

192 DFS (diet) questionnaire: This 26 item food frequency questionnaire was developed
193 specifically to detect variation in saturated fat and added sugar intake. The questionnaire has
194 established reliability and validity (see Francis & Stevenson, 2013, for details). To summarise,
195 dietary intakes of saturated fat and added sugar obtained from an extensive Australian (CSIRO)
196 food frequency question, and from a 4-day Medical Research Council diet diary, both
197 significantly correlated with DFS (diet) scores (r's from 0.36 to 0.71), indicating that higher
198 scores on the DFS equate to higher intakes of saturated fat and added sugar. More recently, we
199 have shown that a skin spectrophotometry estimate of subcutaneous carotenoid levels, which
200 are primarily derived from fruit and vegetable intake, is significantly and negatively associated
201 with DFS (diet) score (r = -0.21; Attuquayefio et al., Submitted), indicating that dietary fruit
202 and vegetable intake is lower in individuals scoring higher on the DFS. The DFS is also
203 reliable, even over fairly extended intervals (22 weeks; r = 0.84).

Procedure

The study protocol was approved by Macquarie University Human Research Ethics Committee and informed consent was provided by all participants. After consenting, participants completed three questionnaires: (1) a biographical questionnaire to obtain age, gender, along with general health questions and ones pertaining to adherence to the pre-experimental instructions; (2) a chemosensory health-screening questionnaire, developed in our lab to identify potential olfactory impairments (history relating to allergies, sinusitis, facial surgery, facial injury, current or recent respiratory infections, current or recent nasal congestion, any past or current problems with taste or smell, current and past smoking history, any history of head injury, and any previous periods of unconsciousness/concussion); (3) a current-state questionnaire, with rating of hunger, thirst, fullness, happiness, sadness, relaxedness and alertness - in that order - on 120mm line scales (anchors Not at all and Very).

Participants then completed, in this order, the following study tasks: (1) Threshold testing with the Sniffin Sticks; (2) Discrimination testing with the Sniffin Sticks; (3) Odour identification testing with the Sniffin Sticks; (4) Gustatory testing; (5) Flavour testing; and (6) Final study measurements. Each is described in more detail below.

Sniffin-sticks test battery: Threshold testing was conducted as per the manual, in all but one regard, as only five sets of reversals were employed. The 16-odour triad discrimination task (using a forced choice oddity [triangle] test) and the 16-item odour identification task (using a four response option forced choice procedure) were both conducted as per the manual.

Gustatory testing: On this test participants sampled and evaluated seven tastants. Five of these were presented in random order (strong and weak sucrose and saline solutions, and citric acid solution), with the salt standard always being the penultimate sample, and the PROP sample being the last to be evaluated. Following instructions on scale usage, participants were asked to pour the whole of the first sample into their mouth and then expectorate, and immediately complete the six evaluations. Evaluations were made on 12cm labelled

magnitude scales (based upon Green et al., 1996, and using the same ratios for the anchors) for intensity, sweetness, bitterness, saltiness, sourness and hedonics (in this last case using a bipolar labelled magnitude scale, based upon Lim, Wood & Green, 2009). Participants then rinsed with water, waited 5s, and then commenced the next trial, repeating this procedure for all of the remaining tastants.

Flavour testing: On this test participants sampled and evaluated 18 solutions presented in randomised order. The same pour-into-the-mouth, sample, spit, rate and rinse procedure was used here as for the gustatory testing. However, participants made a slightly different set of evaluations here, rating intensity, sweetness, fattiness, fruitiness and hedonics, again using labelled magnitude scales.

Final study measures: All participants completed the DFS (diet) scale so as to obtain the most recent estimate of their use of a Western-style diet, with this estimate being used in the analysis. Height and weight were measured to calculate body mass index (BMI).

Analysis

The DFS (diet) score obtained at the end of testing formed the key dietary measure. Its 26 item scores were summed for each participant. This score was then used as a continuous variable in all of the analyses, rather than as a grouping variable (i.e., high vs. low). Treating this score as a continuous variable is more powerful than using it to form groups, as it utilises all of the information in the dietary measure (Preacher et al., 2005).

Threshold scores were the mean of the final four reversals (higher numbers indicate greater sensitivity), and discrimination and identification scores were the number of correct responses out of 16.

For measures using the labelled magnitude scale scores, we found these to more closely approximate to a normal distribution than when a log-transformation was applied and so these data were analysed without further transformation. Three types of score were assembled for

the Gustatory tests: Intensity – from the intensity rating in mm along the labelled magnitude scale; Hedonics, with scores in mm on the hedonic scale being positively signed for liked responses and negatively signed for disliked responses; and Quality – the nominal taste quality (e.g., sweetness for sucrose) minus the mean taste quality scores for the remaining qualities (in the case of sweetness - sourness, saltiness and bitterness). This latter approach to analysing the taste quality ratings is both sensitive to impairments in taste processing (e.g., Stevenson, Miller & McGrillen, 2013) and reduces the number of comparisons necessary to analyse these types of data.

For the Flavour test, all of the ratings were analysed separately, because of interest in certain rating scale specific effects (i.e., odour/taste enhancement and fat suppression). A chemosensory problem score was also calculated, based upon responses to the 12-item chemosensory health-screening questionnaire (scores could vary between 0 and 12, with 1 being given for each response indicative of possible impairment and 0.5 for unsure responses).

Two main analysis approaches were used. The first involved descriptive statistics and then zero order correlations between DFS (diet) score and particular variables of interest. This approach was then followed up in cases where significant relationships with DFS (diet) score emerged, by a further correlation in which the effects of age, gender, BMI and chemosensory problem score (and certain other variables as identified in the text) were partialled out. The second approach was to use ANCOVA (dependent variables being intensity, quality and hedonic ratings, and independent variables being stimulus concentration and/or type), notably on the flavour and taste data. In these analyses DFS (diet) score (transformed into a Z-score) was included as the covariate, which can be thought of as being akin to a continuous between-participant independent variable. This allowed us to test for any heterogeneity in relationships between the covariate and the factors included in each analysis, as well as establishing any relationship between the covariate and the grand mean. This approach was also used in conjunction with the first, to explore particular effects identified a priori as being of interest

(i.e., taste and odour enhancement, fat odour suppression effects). For succinctness, the ANCOVAs are reported in summary form, except where DFS-related effects emerged. Finally, alpha was set at 0.05, with 1-tailed tests for a priori directional hypotheses and with Bonferroni adjusted alpha's for multiple comparisons as described in the Results section.

Results

There were no correlations between age, gender, BMI and DFS (diet) score – see Table 1 for details. While the chemosensory problem score (see Table 1) correlation was non-significant ($p = .095$), it would appear that there is a slightly heightened rate of factors associated with impaired chemosensory function in more frequent consumers of a Western-style diet (i.e., a higher DFS score). There were no significant correlations between hunger, thirst, fullness or mood ratings and DFS (diet) score, suggesting similarity in state at testing. A summary of the key findings, including variance accounted for, is presented in Table 2.

Odour testing

Threshold: Mean butanol threshold was 7.2 (SD = 2.9), with no observed relationship with DFS (diet) score.

Discrimination: Mean odour discrimination score was 11.5 (SD = 2.0), with no observed correlation with DFS (diet) score.

Identification: Mean identification score was 11.5 (SD = 2.5), and there was a significant correlation between this variable and DFS (diet) score ($r = -0.20$, $p < 0.05$, 1-tailed). This relationship was not attenuated when age, gender, BMI, chemosensory problem score, threshold score and discrimination score, were partialled out ($r = -0.24$, $p < 0.05$, 1-tailed). This suggests that greater reported consumption of a Western-style diet is associated with poorer odour identification ability, confirming earlier preliminary findings for identification.

Gustatory testing

PROP: There was a significant correlation between PROP intensity ratings (M = 57.1; SD = 37.5) and DFS (diet) score ($r = 0.20$, $p < 0.05$, 1-tailed). This relationship was not attenuated when partialling out the effects of age, gender, BMI and chemosensory problem score ($r = 0.20$, $p < 0.05$, 1-tailed). This suggests that greater consumption of a Western-style diet is associated with greater sensitivity to bitter tasting PROP.

There was also a significant negative correlation between hedonic ratings for PROP (M = -25.9; SD = 21.0) and DFS (diet) score ($r = -0.21$, $p < 0.05$, 1-tailed). This relationship was not attenuated when partialling out the effects of age, gender, BMI and chemosensory problem score ($r = -0.19$, $p < 0.05$, 1-tailed). Complimentary to the findings above, greater consumption of a Western-style diet is associated with greater dislike for PROP.

Finally, there was no association between taste quality score (i.e., bitter rating minus the mean of the other taste quality ratings) for PROP (M = 53.0; SD = 38.8) and DFS (diet) score, indicating that all participants were readily able to discern its principal taste quality.

Citric acid: There were no significant correlations between DFS (diet) score and citric acid intensity, quality or hedonic ratings.

Sucrose and saline – Intensity: ANCOVA revealed no effects including DFS (diet) score.

Sucrose and saline – Quality: ANCOVA revealed no effects including DFS (diet) score.

Sucrose and saline – Hedonics: A two-way repeated measures ANCOVA, with Tastant (sucrose vs. saline) and Concentration (strong vs. weak), and DFS (diet) score entered as a covariate, revealed main effects of Concentration and Tastant, and a Tastant by Concentration interaction. There was also an interaction between DFS (diet) score and Tastant ($F(1,85) = 6.09$, $p < 0.02$, partial eta-squared = 0.07), indicating that DFS (diet) score correlated with one of the tastant variables significantly more so than with another. DFS (diet) score was

significantly correlated with hedonic ratings for salt solutions (collapsed across Concentration; $r = -.26$, $p < 0.02$; accounting for 6.8% of the variance in the dietary measure), but not with sucrose solutions (collapsed across Concentrations; $r = 0.02$). The relationship between diet and salt solution hedonic ratings was maintained even when partialling out age, gender, BMI and chemosensory problem score, indicating that relatively neutral ratings were provided by participants with a low DFS (diet) score, while those who consumed diets richer in saturated fat and added sugar were more negative in their evaluation.

Flavour testing

Intensity: ANCOVA revealed no effects involving DFS (diet) score.

Sweetness, and sweetness enhancement effects: ANCOVA revealed no effects involving DFS (diet) score.

We then calculated mean linear and quadratic slope coefficients across the three levels of factor Odour, collapsing across Sugar and Fat levels, to determine if the pattern of sweetness enhancement was related to DFS (diet) score. While there was no association with the linear coefficient, the relationship with the quadratic coefficient was significant ($r = -0.21$, $p < 0.05$). Participants with a healthier diet tended to have positively signed quadratic functions, with degree of sweetness enhancement increasing most between the low and high levels of factor Odour. In contrast, participants with a more Western-style diet tended to have negatively signed quadratic functions, with maximal taste enhancement for the lower odour level and minimal enhancement for the higher level. This correlation was attenuated when partialling out the effects of age, gender, BMI and chemosensory problem score ($r = -0.21$, $p = 0.059$).

Fattiness: The fattiness data were analysed with a three-way repeated measures ANCOVA, with Fat level (skimmed vs. full fat milk), Sugar level (low vs. medium vs. high) and Odourant level (zero vs. low vs. high concentration) as within factors and DFS (diet) score as the covariate. There were main effects of Sugar level and Fat level, with the Fat level effect

being moderated by DFS (diet) score ($F(1,85) = 4.58$, $p < 0.05$, partial eta-squared = 0.05). To examine this diet-related effect, we subtracted the mean fattiness rating of all of the skimmed milk samples (M = 35.2) from the mean fattiness rating of all of the full fat milk samples (M = 40.9). There was a significant correlation between DFS (diet) score and this fattiness difference score ($r = -.29$, $p < 0.01$). Poorer discrimination of the two fat levels in terms of a smaller difference score, was reported by participants who habitually ate a diet rich in saturated fat and added sugar. This relationship was not attenuated by partialling out the effects of age, gender, BMI and chemosensory problem score ($r = -0.28$, $p < 0.01$).

Fruity odour ratings, fat suppression and flavour enhancement: ANCOVA revealed no effects involving DFS (diet) score. We also tested if the degree of fat suppression of the cherry odourant was associated with DFS (diet) score, but no diet-related effects emerged.

Hedonics: The hedonic data were analysed using the same ANCOVA design as above. There were main effects of Sugar and Fat level and an interaction between Sugar level and Fat level, and by that between DFS (diet) score, Sugar level, Fat level and Odourant level ($F(4,340) = 3.19$, $p < 0.02$, partial eta-squared = 0.04). To examine the source of this four-way effect we conducted eight further ANCOVA's – Fat and Odourant at each Sugar level (3 analyses), Fat and Sugar at each Odourant level (3 analyses) and Sugar and Odourant at each Fat level (2 analyses). In each case we examined for the interaction between the covariate and the two within participant variables present in each analysis (respectively; Fat by Odourant, Fat by Sugar, Sugar by Odourant), setting alpha at 0.00625 (Bonferonni correction). One interaction effect was detected in this way between Sugar, Odourant and DFS (diet) score in the low fat skimmed milk samples ($p < 0.003$). We then examined this further by looking at the difference in liking ratings between the unodourised and the highly odourised samples (to maximise any differences), at each level of sweetness. These three mean difference scores were then analysed using a one-way repeated measures ANCOVA, with Sugar level as the within factor and DFS (diet) score as the covariate. There was one effect, a significant

interaction between the covariate and Sugar level ($F(2,170) = 5.46$, $p < 0.005$, partial eta-squared = 0.06). We then examined for the source of this effect by comparing the correlation between the DFS (diet) score and each of these three difference scores using the Williams test, with alpha set at 0.017 (Bonferroni correction). The difference emerged between the medium and high sugar level, and DFS (diet) score, with a resultant correlation of 0.32 ($p < 0.005$). In skimmed milk, the addition of the odourant enhanced pleasantness most in the medium sugar level for participants who consumed a more healthful diet, while the odourant enhanced pleasantness most in the high sugar level for participants who consumed a Western-style diet. This correlation was not attenuated, when partialling out the effects of age, gender, BMI and chemosensory problem score ($r = 0.31$, $p < 0.005$).

Discussion

The aim of this study was to examine the chemosensory correlates of a Western-style diet. Several findings emerged (see Table 2 for summary). On the olfactory tests of threshold, discrimination and identification, only an association between DFS (diet) score and identification was observed, supporting our previous unpublished findings for identification, but not for discrimination. We also expected to observe differences relating to PROP perception and these too were noted. Participants who consumed a Western-style diet judged bitter tasting PROP to be more intense and liked it less than those who reported consuming a diet lower in saturated fat and added sugar. The study also explored whether certain aspects of flavour perception might be related to diet. Only one effect was observed relating to sweetness enhancement (albeit weakened when the control variables were partialled out), with no effects for odour enhancement or fat induced odour suppression. The Flavour and Taste tests both revealed some additional diet-related effects. Consumers of a Western-style diet were poorer at discriminating the fat levels used in the experiment and their hedonic responses to some of the flavour and taste stimuli also differed. The Flavour and Taste tests yielded no diet-related

differences in intensity perception this being consistent with many previous reports (e.g., Bertino et al., 1986; Mattes, 1985; Moskowitz et al., 1975).

Before discussing these findings it is important to consider their limitations. One potential limitation relates to the small to moderate effect sizes observed here. First, these effects could be an artefact of multiple comparisons, but this suggestion would seem less likely in that several findings were anticipated (e.g., PROP, fat discrimination, odour identification). Second, it could be concluded that even if the observed effects are genuine and replicable, their impact on food choice and ultimately human health would be correspondingly small. However, this might not be the case, as effect size does not directly relate to an effect's importance (e.g., McCartney & Rosenthal, 2000). Small effects can exert large impacts especially at the population level, and more so if multiple small effects independently influence behaviour. Third, it has to be born in mind that measurement error is a significant issue in this field. Dietary intake measures are noisy, laboratory based measures of perceptual ability (e.g., watery taste solutions; non-food odour for threshold) may not fully relate to the way these abilities manifest outside of the laboratory, and there may be disagreements between studies due to differences in the measures used (see Cox et al., 2016; Mattes, 1985). While we note that the techniques used here were not exceptional relative to other studies in the area, we did attempt to use the standardised procedures when available (i.e., Sniffin sticks; PROP protocol).

A further consideration is whether some other variable(s) might be mediating the observed relationships between diet and chemosensory performance. In epidemiological studies, dietary associates of psychological variables (notably relating to cognition) are often mediated by socioeconomic status (SES) and especially by education (e.g., Akbaraly et al., 2009). It would seem unlikely that SES would be a major factor in moderating the chemosensory variables tested here, but even if it were, our sample were all receiving a university education in a catchment that draws from a wealthy area of Sydney, making it fairly homogenous with regard to SES. Gender is clearly another variable that may affect diet (e.g.,

Rozin, Bauer & Catanese, 2003) and chemosensory ability (e.g., Dempsey & Stevenson, 2002). While we found no relationship between DFS (diet) score and gender in the sample used here, this variable was nonetheless included in all of the partial correlations. The same also applies to age and BMI, which are factors also linked to both diet and chemosensory ability. A further control factor used in the partial correlation analyses was the chemosensory problem score, which tended ($p = 0.095$) to be somewhat higher in participants who consumed a Western-style diet. Finally, while we did not explore cultural background as a factor, this could be important in future studies. Early experience with flavours and smells within a particular culture, may affect later processing of these stimuli as an adult (e.g., Poncelet et al., 2010), providing a further factor that might affect diet-perception relationships.

In the Introduction we suggested that people with poorer olfactory abilities might gravitate to less healthy food choices. The basic rationale for this assertion is that a major component of flavour perception comes from olfaction (Stevenson, 2014), and if this input is weakened, participants might compensate by choosing diets that offer greater taste and somatosensory impact. Some support for this idea came from the finding in anosmics that dietary shifts are made towards more energy dense foods. However, anosmia appears to have divergent effects on food intake and BMI, with some anosmic participants reporting both BMI and food intake reductions and others the reverse (e.g., Ferris & Duffy, 1989; Merkonidis et al., 2015). The main problem with the idea that dietary choices may be shifted towards less healthy alternatives if olfactory ability is poorer, is that we only found evidence of poorer odour identification ability. Differences in threshold and discrimination would have provided far more robust support to this idea, because they would have suggested that frequent consumers of a Western-style diet could not properly detect and distinguish odours. Perhaps then poorer odour identification ability is just a consequence of reduced exposure to food-based odours – noting their predominance in the Sniffin sticks test battery (e.g., eating fewer fruits and vegetables, less buying, cooking and preparing food, etc).

A further perspective is available on the odour identification data. Animal studies indicate that the hippocampus become rapidly and adversely affected by a Western-style diet (e.g., Beilharz, Maniam & Morris, 2014). The hippocampus may be especially sensitive to environmental insults (such as from diet) because it exhibits high synaptic plasticity and neurogenesis (Murray & Holmes, 2011; Walsh & Emerich, 1988). The olfactory system might be similarly vulnerable, as it too demonstrates high synaptic plasticity and neurogenesis (Lledo, Alonso & Grubb, 2006). Indeed, recent animal work has shown olfactory impairments following a high fat diet (Thiebaud et al., 2014). As human olfactory identification is supported at least in part by the hippocampus (e.g., Kjelvik et al., 2012) it is plausible that consuming a Western-style diet could also cause impaired identification.

For the PROP-related findings, the direction of the causal arrow would seem far more assured. There are many studies (see Feeney, 2011; Hayes et al., 2013, for reviews) that show a weak to moderate relationship ($r \approx 0.2$) between intake of cruciferous vegetables and PROP sensitivity, as measured in one of several different ways. Presumably this relationship occurs because the bitterness of these vegetables is unpleasantly intense to individuals who have a genetic predisposition to strongly experience PROP bitterness. The effects found here are of broadly similar magnitude to the vegetable-PROP literature, but are interesting for two additional reasons. First, they are novel because the dietary variable here is generic, unlike much of this literature, which has focussed on specific foods likely to be impacted by PROP sensitivity. Second, while greater PROP sensitivity might reduce fruit and vegetable intake, it has also been argued that it increases sensitivity to sweet and fatty tastes due to the greater number of fungiform papillae (e.g., Bartoshuk et al., 2006; Hayes & Duffy, 2007). This may result in a PROP-sensitive person preferring lower concentrations of sweet and fatty tastes, which might moderate some of the effects on fruit and vegetable intake (Bartoshuk et al., 2006). However, few studies have examined actual fat intake and PROP perception, and the only finding to emerge has been of greater fat intake in PROP sensitive people (Yackinous &

Guinard, 2002). Nonetheless, other studies suggest that the relationship between PROP sensitivity and sweet and fatty taste perception may be more nuanced, with other factors affecting these relationships including quinine sensitivity (Hayes & Duffy, 2008). In sum, it seems likely that the positive association revealed in this study between PROP sensitivity and DFS (diet) score arises because the main causal relationship is one in which dislike of bitter tastes produces preferences for diets low in plant based foods.

It is clear from laboratory studies that there is considerable individual variation in fat perception (e.g., Tucker & Mattes, 2013), but it is far less clear how this impacts on dietary choice and fat intake, as findings here have been mixed (e.g., Cooling & Blundell, 2001). Here, we found that better fat discrimination between the skimmed and full fat milk samples, indicated by a larger difference in fattiness ratings, was associated with DFS (diet) score. Specifically, participants reporting greater intake of saturated fat were the poorest discriminators. Liang et al., (2007) made a similar observation when correlating performance on a laboratory fat discrimination task with self-reported food intake, in a much larger African-American sample. Poorer discriminative performance was associated with greater intake of high fat foods, sources of added fat and sugar, and reduced fat foods. It is currently unclear whether these effects of fat discrimination are a consequence of dietary exposure or result from pre-existing differences in sensory physiology. There is evidence for both, as controlled exposure to low fat foods seems to improve various aspects of fat perception (threshold, ranking of fat content; Stewart & Keast, 2012; and see Newman, Haryono & Keast, 2013), while as noted above, PROP sensitivity, and certain receptor gene variants can also affect fat perception (e.g., CD36 receptor; Keller et al., 2012). Finally, these types of individual differences in fat perception may be practically significant, as a recent laboratory study found that poorer fat perception was associated with greater food intake (Keast et al., 2014).

In examining the perceptual correlates of habitual diet there has been very little interest in flavour perception. Here we focussed on two classes of flavour-related interaction effect,

both of which are psychologically based (Stevenson, 2009). The first concerned interactions between taste and smell, and the ability of tastes to augment perception of certain odours and vice versa (Frank & Byram, 1988; Von Sydow et al., 1974). The second, relates to the ability of fats to suppress perception of odours in the mouth (Bult, de Wijk & Hummel, 2007). We found no evidence for diet-related differences in odour-fat interactions, but we did find an effect for sweetness taste enhancement (i.e., where, in the mouth, a sweet taste is judged to taste sweeter in the presence of certain odours) - noting that this was only marginally significant after partialling out the control variables. People reporting a Western-style diet tended to demonstrate taste enhancement effects for the weak odour concentration, but not for the strong, while participants with a healthier diet reported a small degree of enhancement for the weak odour concentration and most for the strong concentration. One way of understanding the origin of odour-taste interactions is that they are a product of learning (e.g., Stevenson, Boakes & Prescott, 1998). On this basis, when tastes are present in the mouth, participants with Western-style diets may tend to experience typically weaker oral odour sensations than participants with a healthier diet. Thus weaker smells may be more likely to enhance tastes than stronger smells in frequent consumers of a Western-style diet. There are two reasons to suspect that exposure to weaker oral olfactory percepts actually occurs in habitual consumers of a Western-style diet. Not only may their greater fat intake suppress oral odour perception they may also consume fewer foods that have high volatile contents (i.e., fruits and vegetables). Needless to say, we only tested one oral odourant, one tastant and one fatty vehicle, but the observation of an effect here suggests that dietary associates of flavour perception may not be hard to find.

Two observed effects related to taste and flavour hedonics. First, the salt solutions were judged as less pleasant by more frequent consumers of a Western-style diet. This finding is surprising as higher salt concentrations are a feature of this type of diet. However, saline solutions are infrequently experienced outside of the laboratory and so there dislike could

reflect greater neophobia in more frequent consumers of a Western-style diet – something that has been observed before (Siegrist et al., 2013). In addition, greater PROP sensitivity is also associated with reduced liking for aqueous salt solutions (Hayes, Sullivan & Duffy, 2010). Second, hedonic differences also emerged on the flavour analysis. Cherry odourant enhanced the pleasantness of skimmed milk most successfully in the medium sugar level for those who ate a healthier diet, and at the higher sugar level for those who consumed a Western-style diet. As the higher sugar level generates both a sweeter taste and a fattier mouthfeel, this may be more appealing to participants who consume fattier and sweeter foods.

Finally, we note that many elderly people have impaired chemosensory perception (e.g., Doets & Kremer, 2016), yet this appears to have relatively little impact upon their enjoyment of food (e.g., Arganini & Sinesio, 2015; Kremer et al., 2007). This might suggest that sensory differences have little impact on dietary choice. We suspect this conclusion may be less likely to apply to younger people. First, hedonic reactions to food have a learned component. Elderly consumers - in contrast to younger ones - may be more reliant on such learned reactions and thus less susceptible to the effects of sensory loss. Second, sensory factors that favor unhealthy food choices may aid establishing a dietary pattern that then becomes habitual, making it more resistant to change during ageing. Third, to the extent that certain sensory differences are innate, these may affect parental dietary choice, which in turn will shape the foods the child is exposed to. Importantly, we note that as yet there has been no systematic examination of how broad sensory differences in young adults may affect food choice – in contrast to the studies completed for the elderly (e.g., the European Union Healthsense project).

In conclusion, we set out to examine chemosensory correlates of a Western-style diet. We observed differences in odour identification ability, PROP sensitivity, fat discrimination, sweetness taste enhancement, and taste and flavour hedonics, but no differences in odour discrimination or threshold, in perception of taste intensity/quality (excluding PROP) or the

ability of fats to affect flavour perception. Most of the observed relationships were of small to moderate effect size. While there manifestation in habitual consumers of a Western-style diet would generally seem to work against eating a more healthful diet, whether they are a cause or a consequence of dietary choices remains to be established for most of the effects reported here.

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Table 1: Descriptive statistics and Pearson correlations between participant characteristics, DFS (diet) score

Variable	Descriptive statistics	Correlation with DFS (Diet) score
DFS (diet) score	M = 59.9, SD = 13.7, range 37-104	
Gender	38 men/49 women	0.10
Age	M = 20.8, SD = 3.3, range 18-31	-0.04
BMI	M = 22.3, SD = 3.1, range 16.0-32.7	0.00
Chemosensory problem score	M = 1.0, SD = 1.0, range 0-4	0.18

Table 2: Chemosensory correlates of a Western-style diet (WS-D) alongside the variance accounted for by each effect

Test	Correlate	Variance accounted for	Finding
Sniffin Sticks			
	Odour identification	4.0%	Poorer in consumers of a WS-D
Gustatory tests			
	PROP sensitivity	4.0%	Greater in consumers of a WS-D
	PROP disliking	4.4%	Greater in consumers of a WS-D
	Salty taste disliking	6.8%	Greater in consumers of a WS-D
Flavour test			
	Sweetness enhancement		
		4.4%	Maximal enhancement at lower odourant level in consumers of a WS-D
	Fat discrimination	8.4%	Poorer in consumers of a WS-D
	Flavour hedonics	10.2%	Odour increased pleasantness of skimmed milk most at high sugar-levels in consumers of a WS-D