Received: 31 May 2021 | Revised: 26 August 2021 | Accepted: 27 August 2021

DOI: 10.1111/joss.12715

ORIGINAL ARTICLE

Journal of Sensory Studies

WILEY

Nonlinear association between chemosensory dysfunction and body mass index

Ben Chen[1,2] | Carla Masala[1,3] | Anna Oleszkiewicz[1,4] | Verena Englmaier[1] | Nadine Gunder[1] | Susanne Menzel[1] | Antje Haehner[1] | Thomas Hummel[1]

[1]Interdisciplinary Center Smell and Taste, Department of Otorhinolaryngology, Medical Faculty Carl Gustav Carus, TU Dresden, Dresden, Germany

[2]Memory Clinic, Department of Geriatric Psychiatry, The Affiliated Brain Hospital of Guangzhou Medical University (Guangzhou Huiai Hospital), Guangzhou, China

[3]Section of Physiology, Department of Biomedical Sciences, University of Cagliari, Cagliari, Italy

[4]Institute of Psychology, University of Wroclaw, Wroclaw, Poland

Correspondence
Ben Chen, Interdisciplinary Center Smell and Taste, Department of Otorhinolaryngology, Medical Faculty Carl Gustav Carus, TU Dresden, Dresden, Germany.
Email: chenbenpielo@sina.com

Abstract

Chemosensory (gustatory and olfactory) dysfunction contributes to obesity, but the association between body mass index (BMI) and chemosensory dysfunction are inconsistently reported. The present study included 4,390 subjects at a Smell and Taste Clinic. Results suggested that both the obesity class II group (BMI ≥ 35) and underweight group (BMI < 18.5) exhibited impaired taste function compared with the normal weight group ($p < .05$). Comparing with the other groups, the obesity class II group exhibited a higher proportion of impaired bitter identification (8.6%), and the underweight group showed a higher proportion of impaired salty identification (7.9%). When investigating differences for individual tastes, subjects with impaired bitter identification had higher BMI ($t = 2.79$, $p = .005$) and lower olfactory scores ($p < .05$) compared with those with intact bitter identification. Finally, reduced taste scores are associated with an increased BMI ($r = -.04$, $p = .022$). This correlation becomes more pronounced with age ($F = 1.42$, $p < .001$).

Practical Application

The nonlinear association between chemosensory dysfunction and BMI suggested that maintaining the gustatory and olfactory function is of significance for normal metabolism. In obesity regulating bitter taste appears to be more important than the other tastes.

1 | INTRODUCTION

Obesity, a clinical condition characterized by an increased body mass index (BMI), becomes an important public health problem because of its high prevalence in the population and their link with serious health morbidities such as hypertension, type 2 diabetes, hypercholesterolemia, cardiovascular disease, and certain types of cancers (Tsai & Bessesen, 2019). Obesity is fueled by individual factors, nutrition transition, and increasingly sedentary lifestyles that lead to an excessive caloric intake. Among individual factors, chemosensory function (gustation and olfaction) plays a significant role in food preferences, choices, and thus, consumption (McCrickerd & Forde, 2016), but their relationships are not yet fully understood.

Taste allows for identification and consumption of appetitive substances, and avoidance of potentially toxic and unpleasant compounds (Gutierrez, Fonseca, & Simon, 2020). High taste acuity may reduce dietary overconsumption and reduce the risk for obesity, while gustatory dysfunction may lead to high calorie diet and obesity (Dotson, Shaw, Mitchell, Munger, & Steinle, 2010). Previous studies suggested that decreased taste sensitivity is related to increased BMI (Vignini et al., 2019) and that individuals with obesity exhibited significant change of taste preference (Hardikar, Hchenberger, Villringer, &

Ohla, 2016; Pepino, Finkbeiner, Beauchamp, & Mennella, 2010) and a higher electrogustometry threshold (Park et al., 2015). Interestingly, underweight individuals were also associated with poor appetite and low taste sensitivity to bitter taste (Fuchida et al., 2013). However, previous evidence does not consistently support the notion that obese individuals have altered taste sensitivity, or associates taste-specific impairment with obesity (Ribeiro & Oliveira-Maia, 2021). This inconsistency may result from their limited sample sizes and heterogeneity of taste assessments. In addition, it remains unclear what degree of obesity may significantly affect the gustatory function.

Olfaction is known to play a major role in food choice, and olfactory dysfunction is closely related to BMI changes (Peng, Coutts, Wang, & Cakmak, 2019). Both weight gain and weight loss have been reported as consequences of olfactory dysfunction (Aschenbrenner et al., 2008; Aschenbrenner, Scholze, Joraschky, & Hummel, 2008). Individuals with smell impairment repeatedly complain that food is less enjoyable and flavorful, and that inability to perceive food-related odors corrupts their eating and cooking habits (Croy, Nordin, & Hummel, 2014). However, also the link between olfactory perception and weight are inconsistent. While one study reported reduced odor sensitivity and odor discrimination to be associated with higher BMI (Simchen, Koebnick, Hoyer, Issanchou, & Zunft, 2006), another found obese individuals to exhibit significant reduction in odor sensitivity but not in odor discrimination or identification (Fernandez-Garcia et al., 2017). Age may be one of the factors explaining these discrepant findings. It has been demonstrated that for individuals younger and older than 65 years, the associations of BMI and olfactory abilities were different, suggesting age may have an interactive effect with BMI on olfactory function (Simchen et al., 2006).

Collectively, BMI change may be associated with gustatory and olfactory dysfunction, but the related clinical evidence is not consistent. The present study aimed to explore the relationships between chemosensory dysfunction and BMI in a large sample ($n = 4{,}390$) by using taste spray and Sniffin' Sticks. Subjects were grouped by different BMI degrees, and their gustatory and olfactory function was compared. Additionally, the potential effect of age on the relationship between chemosensory dysfunction and BMI were analyzed.

2 | EXPERIMENTAL

2.1 | Participants

Four thousand three hundred and ninety patients (2,564 women, 1,826 men) were included in this retrospective study, with an age range from 18 to 95 years and a mean age of 56.6 years (*SD* 13.8). All patients were seen in the Smell and Taste Clinic at the Department of Otorhinolaryngology of the TU Dresden.

The inclusion criteria were an age of 18 years and older, and the ability to comprehend and adequately perform the test procedures. The following exclusion criteria had been defined: head trauma, dementia, neurodegenerative disorders, and psychiatric conditions interfering with chemosensory functions.

2.2 | Procedure

The following procedures were performed in all patients: (a) collection of structured medical history and (b) assessment of gustatory and olfactory function. The clinical documentation for each patient included age, sex, body mass index (BMI [kg/m^2]: self-reported weight [in kg] divided by height squared [in m^2]), duration of chemosensory dysfunction (in months), and current medications. Smoking was not consistently recorded. The classification of the BMI was performed according to World Health Organization regional office for Europe: <18.5 underweight ($n = 63$), 18.5–24.9 normal weight ($n = 1921$), 25–29.9 pre-obesity ($n = 1{,}664$), 30–34.9 obesity class I ($n = 556$), 35–39.9 obesity class II ($n = 159$), and >40 obesity class III ($n = 26$) (WHO, 1995). The obesity class III group was excluded in the analyses because of the limited sample size. The retrospective study was approved by the Ethics Committee at the "Technische Universität Dresden," Germany (EK 251112006).

2.3 | Assessment of gustatory function

All olfactory and gustatory assessments were carried out in a ventilated room through the daytime (9 a.m. to 5 p.m.). All participants were instructed to not eat, smoke, and to drink only water 1 hr prior to the experiment. Taste function was evaluated by using the Taste Sprays (Welge-Lussen, Dorig, Wolfensberger, Krone, & Hummel, 2011). The "Taste Sprays" are rapid screening test for the four basic tastes, applied to the oral cavity at suprathreshold concentrations. Subjects have to identify the taste from a list with four items (sweet, sour, salty, bitter). We used the tastants sucrose (1 g in 10 g aqua; sweet), citric acid (0.5 g in 10 g aqua; sour), sodium chloride (0.75 g in 10 g aqua; salty), and quinine hydrochloride (0.005 g in 10 g aqua; bitter). Each spray was applied twice. Subjects opened their mouth, put out their tongue, and a spray (volume approximately 150 μL) was applied. Then they were allowed to take their tongue inside the mouth again and to move it. Subjects correctly identifying the bitter spray were defined as "intact bitter identification," and those who wrongly identified the bitter spray were defined as "impaired bitter identification." This approach was also used for other tastes. The total score ranges from 0 to 4 points. The taste sprays have been used twice to avoid false-negative responses.

2.4 | Assessment of olfactory function

Orthonasal olfactory function was evaluated using the Sniffin' Sticks test (Hummel, Sekinger, Wolf, Pauli, & Kobal, 1997). Three different olfactory functions were assessed in the following order: odor threshold (OT), odor discrimination (OD), and odor identification (OI). OT was determined for (the rose-like) phenyl ethyl alcohol (PEA) with 16 stepwise dilutions starting at a 4% solution (dilution ratio 1:2 in propylene glycol). OT was measured using the single-staircase technique based on a three-alternative forced-choice task and the subjects total score ranged from 1 to 16. OD was assessed over 16 trials. For each trial three pens were presented, two containing the same odor and the third containing the target odor. Possible scores in OD ranged from 0 to 16 points. OI was assessed presenting 16 common odors with four verbal descriptors in a multiple forced-choice format (three distractors and one item describing the target odor). Possible scores in OI ranged from 0 to 16 points. The interval between odor presentations was 20–30 s. A total score (OT + OD + OI = TDI) was calculated.

2.5 | Statistical analysis

Statistical analyses were performed using SPSS 25 software (IBM, Armonk, NY). The level of statistical significance was set to .05. The analysis of covariance (ANCOVA) was used to explore the difference of OT, OD, OI, TDI, and taste scores in various BMI degrees, controlling for age and sex, and least significant difference (LSD) was used for post hoc comparison. Chi-square test was used to compare the distribution of impaired taste qualities (sweet, bitter, sour, and salty) in various BMI degrees. Independent sample *t* test was used to compare the BMI and olfactory scores between subjects with or without impaired taste identification (sweet, bitter, sour, and salty). The partial correlation analysis was used to explore the relationships between BMI and taste, olfactory scores, controlling for age and sex. The stepwise multiple linear regression analysis was used to further explore the relationships between BMI and taste, olfactory scores. In each step of the stepwise multiple linear regression analysis, the control variables included age and sex. Variables with $p > .10$ were excluded in the next step, and variables with $p < .05$ were able to enter the model. General linear model was used to explore the possible moderated effect of age or sex on the relationship between BMI degrees and chemosensory function (taste scores, OT, OD, OI, and TDI).

3 | RESULTS

The demographic information of the five BMI degrees was listed in Table 1. The ANCOVA model showed that the BMI degrees significantly affected the taste scores ($F = 2.43$, $p = .046$), and the post hoc comparison showed that both the underweight and the obesity class II subjects exhibited lower taste scores than the other three groups ($p < .05$) (Figure 1). In addition, the BMI degrees exhibited no significant effect on the OT ($F = 1.70$, $p = .15$), OD ($F = 0.44$, $p = .78$), OI ($F = 0.19$, $p = .95$), and TDI scores ($F = 0.44$, $p = .78$).

The obesity class II group exhibited higher proportion of impaired taste of bitter than the normal weight group and obesity class I group ($\chi^2 = 16.4$, $p = .006$). There was no difference in proportion of taste impairment across the BMI groups for sweet ($\chi^2 = 1.17$, $p = .95$), salty ($\chi^2 = 10.95$, $p = .052$), and sour ($\chi^2 = 4.80$, $p = .44$) identification. In the post hoc comparison, the obesity class II group exhibited a higher proportion of impaired bitter identification than the normal weight group and obesity class I group. Moreover, the underweight group exhibited a higher proportion of impaired salty identification than the other four groups (Figure 2).

Subjects with impaired bitter identification exhibited higher BMI and lower olfactory scores (OD, OI, and TDI) than those with intact bitter identification. Additionally, subjects with impaired sweet identification exhibited lower olfactory scores (OD, OI, and TDI) than those with intact sweet identification. Moreover, subjects with impaired salty or sour identification exhibited lower OD scores than those with intact salty or sour identification (Table 2).

The partial correlation analysis suggested that BMI was weakly associated with OT ($r = -.031$, $p = .039$), TDI ($r = -.032$, $p = .034$), and taste scores ($r = -.036$, $p = .022$), but not OD and OI ($p > .05$). The regression analyses suggested that BMI was associated with taste scores ($\beta = -.035$, $t = -2.246$, $p = .025$, 95%CI [-0.550, 0.037], $R = 0.035$).

The general linear model showed that BMI*age had a significant effect on taste scores ($F = 1.42$, $p < .001$), suggesting that age had a moderating effect on the relationship between BMI and taste scores (the correlations increased with age) (Figure 3). There was no significant effect of BMI*age on olfactory scores (OT, OD, OI, and TDI) ($p > .05$). Additionally, there was no significant interactive effect of BMI*sex on taste and olfactory scores ($p > .05$).

4 | DISCUSSION

The present study explored the association between BMI and chemosensory dysfunction in a large sample population of patients reporting chemosensory impairments. The main findings were (a) the obesity class II group and the underweight group exhibited impaired taste function compared with the normal weight group. (b) The obesity class II group exhibited a higher proportion of impaired bitter identification, and the underweight group exhibited a higher proportion of impaired salty identification. (c) Subjects with impaired bitter identification exhibited higher BMI and lower olfactory scores, and OD scores were affected by all kinds of impaired taste. (d) The increased BMI was weakly associated with reduced taste scores, and this correlation increased with age.

TABLE 1 Demographic information of subjects with different BMI degrees

	Underweight	Normal weight	Pre-obesity	Obesity class I	Obesity class II	*F*	*p*
Age	57.1 ± 19.5	54.2 ± 15.0	58.6 ± 12.5	59.9 ± 11.0	58.65 ± 11.2	28.52	<.001
Male/female	7/56	681/1,240	851/812	326/230	42/97	125.68	<.001

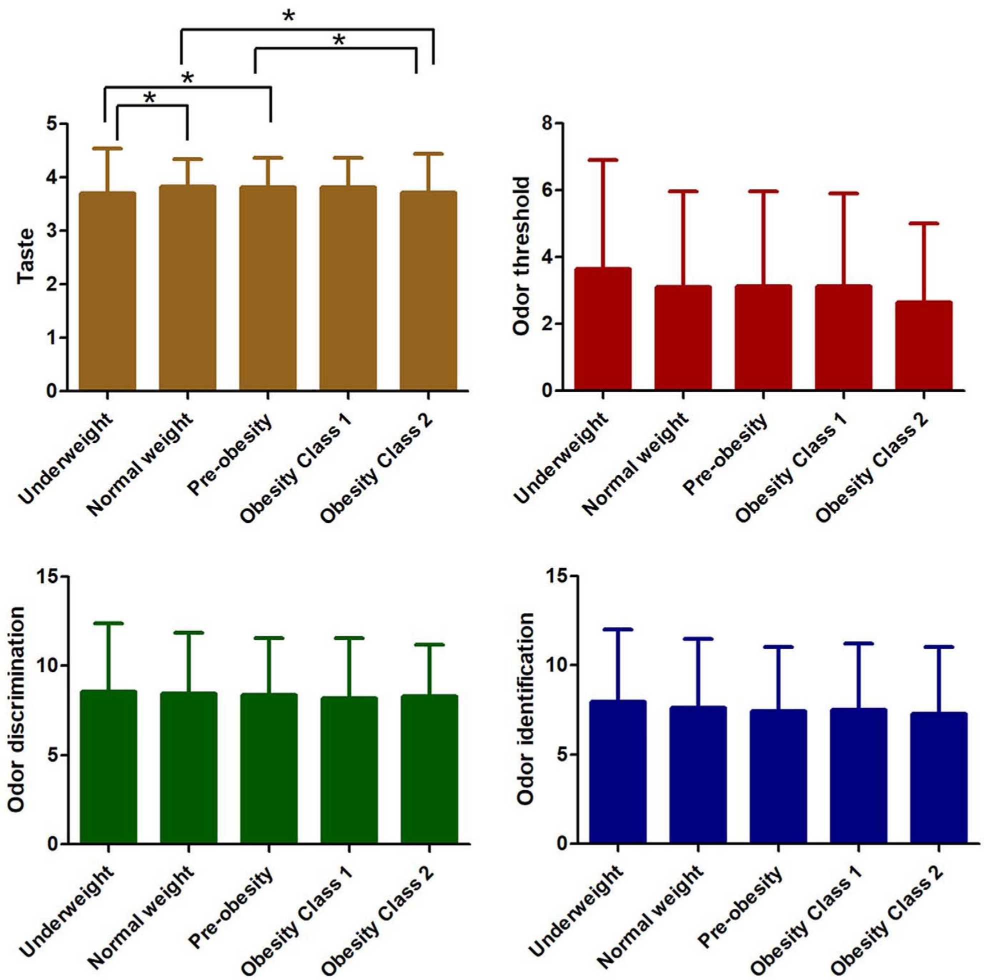

FIGURE 1 Comparison of gustatory and olfactory scores in individuals with different BMI degrees. The classification of the BMI was performed according to World Health Organization regional office for Europe: <18.5 underweight, 18.5–24.9 normal weight, 25–29.9 pre-obesity, 30–34.9 obesity class I, 35–39.9 obesity class II

Previous studies suggested that both overweight and underweight were associated with gustatory dysfunction (Aschenbrenner, Hummel, et al., 2008; Aschenbrenner, Scholze, et al., 2008; Naka, Riedl, Luger, Hummel, & Mueller, 2010; Skrandies & Zschieschang, 2015), but they separately focused on the overweight or underweight subjects. The present study compared taste scores between different BMI degrees and confirmed their nonlinear relationship. On the one hand, normal gustatory function is needed for normal intake of food and healthy nutrition, and gustatory dysfunction may lead to poor appetite and malnutrition (Fuchida et al., 2013). On the other hand, poor taste acuity may change eating behavior and lead to dietary overconsumption, which increases the risk for obesity (Ribeiro and Oliveira-Maia, 2021). Additionally, among various overweight groups, only the obesity class II group exhibited reduced taste scores, suggesting the gustatory function was notably affected only when the overweight reached a certain degree.

Interestingly, subjects in the obesity class II group exhibited impaired bitter identification, and subjects in the underweight group exhibited impaired salty identification. Bitter taste not only plays a protective role in the body by triggering an adverse reaction to spoilt foods and potentially harmful toxins, but is also involved in modulating dietary intake of other foods (Turner et al., 2018). Wang et al. suggested that bitter compounds intake may lead to weight loss by several mechanisms, and the gastrointestinal enteroendocrine cell, gastrointestinal smooth muscle cells, gut-brain axis and adipose tissue may play important roles (Wang, Liszt, & Depoortere, 2020). Instead, individuals with impaired bitter identification may decrease bitter compounds intake and increase carbohydrate intake, leading to weight gain (Duffy, 2004). Type 2 family of taste receptors (T2Rs), an important mediator of bitter taste, has been reported to be involved in imbalanced gastrointestinal microbiome and an increased risk for obesity (Turner et al., 2018). In the present study, the importance of bitter taste is also suggested by the higher BMI in subjects with impaired bitter identification compared with those with intact bitter taste. Such differences were not found when subjects were grouped by other kinds of taste (sweet, sour, and salty). This is consistent with the idea that bitter taste acuity may be a marker for general taste acuity (Feeney et al., 2011; Lim et al., 2008; Turner et al., 2018), and subjects with higher sensitive to bitter may be more sensitive to other tastes, eventually leading to reduced calorie intake.

Previous work also suggested that an underweight status was associated with impaired bitter identification in middle- to old-aged nursing home residents (Fuchida et al., 2013), which are in contrast to the present result that the underweight group exhibited a higher

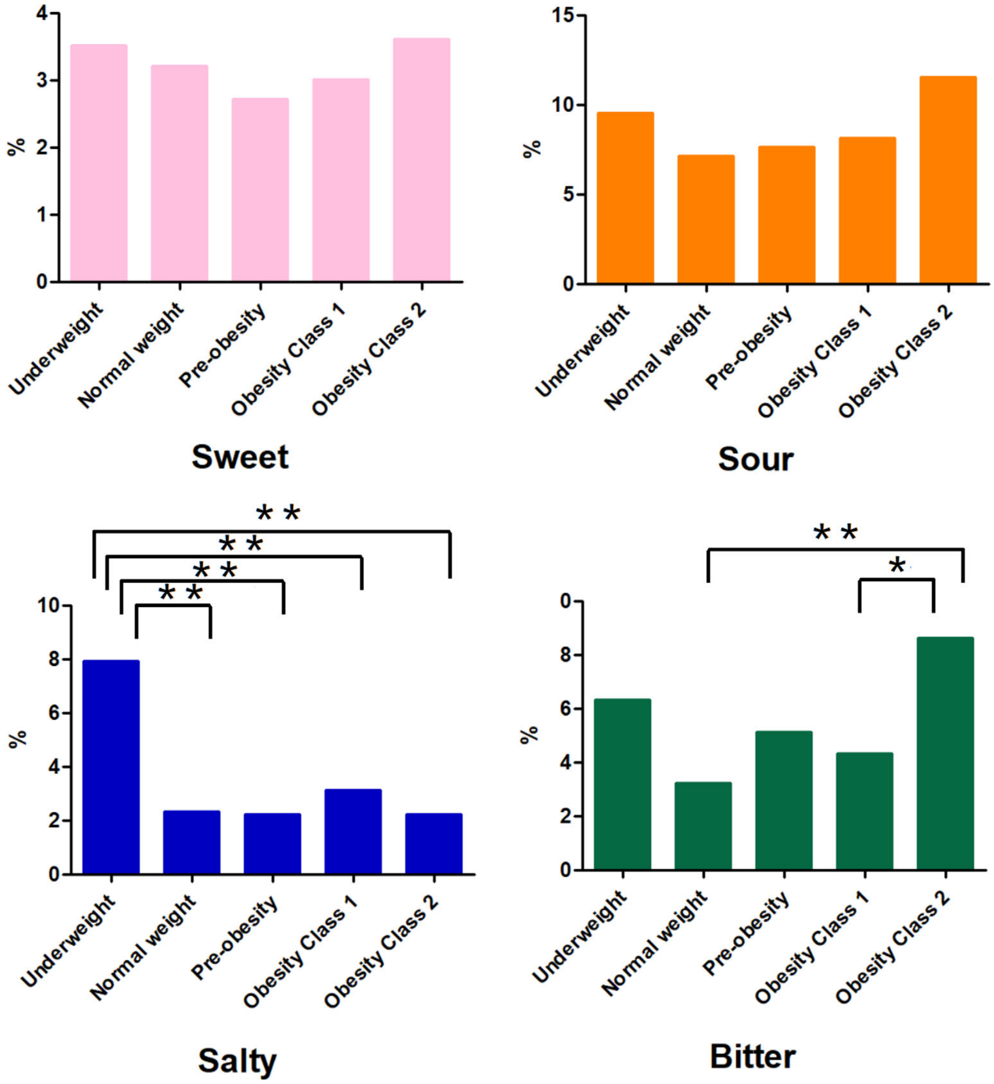

FIGURE 2 Proportion of different kinds of taste dysfunction in in individuals with different BMI degrees. The classification of the BMI was performed according to World Health Organization regional office for Europe: <18.5 underweight, 18.5–24.9 normal weight, 25–29.9 pre-obesity, 30–34.9 obesity class I, 35–39.9 obesity class II

proportion of impaired salty identification. On the one hand, the present subjects came from a Smell and Taste clinic, and their age ranged from 18 to 95, which is different from the previous study. On the other hand, salt is very important in daily diets, and the impaired salt identification may lead to picky eating and increase the risk for underweight. The difference between the present results and previous research (Fuchida et al., 2013) may also simply reflect the fact that tastes dysfunction can have different consequences, depending on context. In overall healthy people, taste dysfunction appears to be related to an increase in body weight, while the opposite seems to be the case in older people with a higher degree of frailty.

The higher proportions of impaired identification of sweet and sour in obesity class II group did not reach a level of significance, suggesting they may be less associated with changes of BMI compared with taste of bitter and salty. Future studies using more elegant taste assessments may provide a deeper understanding about the relationship between BMI and taste of sweet and sour. Collectively, normal gustatory function is important in maintaining balanced diet and normal BMI.

Except from gustatory dysfunction, BMI degrees was negatively associated with OT but not OD and OI, and OT of the obesity class II group was lower compared with the other groups, which was consistent with the previous studies (Fernandez-Garcia et al., 2017; Simchen et al., 2006). This result suggested that obesity may be more associated with peripheral impairment instead of higher-order dysfunction of the olfactory system. Obesity is often associated with major metabolic and hormonal deficits, such as mild hyperglycaemia, glucose intolerance, hyperinsulinaemia, insulin resistance, and hyperleptinemia (Peng et al., 2019). Interestingly, olfactory dysfunction may also act as a protective factor after weight gain. Riera et al. hypothesized that loss of adult olfactory neurons protects against diet-induced obesity, and loss of smell after obesity also reduces fat mass and insulin resistance. Conversely, loss of insulin-like growth factor-1 receptors (IGF1R) in olfactory sensory neurons (OSNs) improves olfaction, and loss of IGF1R in OSNs increases adiposity and insulin resistance (Riera et al., 2017). Overall, these findings suggest that the relationship between olfactory dysfunction and change of BMI is nonlinear.

Previous studies suggested that age might have an interactive effect with BMI on olfactory function (Simchen et al., 2006), which

TABLE 2 Comparison of BMI and olfactory scores when grouping the subjects according to various kinds of taste dysfunction

	n	BMI	Odor threshold	Odor discrimination	Odor identification	TDI
Impaired bitter identification	186	26.7 ± 4.4	2.9 ± 2.8	7.4 ± 3.6	6.7 ± 4.0	16.9 ± 8.9
Intact bitter identification	3,966	25.9 ± 4.1	3.1 ± 2.8	8.4 ± 3.3	7.6 ± 3.7	19.0 ± 8.3
t		2.786	−0.835	−4.128	−3.160	−3.480
p		**.005****	.404	**<.001*****	**.002****	**.001**
Impaired sweet identification	129	26.1 ± 4.2	2.6 ± 2.7	7.2 ± 3.7	6.8 ± 4.1	16.5 ± 8.8
Intact sweet identification	4,023	25.9 ± 4.11	3.1 ± 2.8	8.4 ± 3.3	7.5 ± 3.7	19.0 ± 8.3
t		0.606	−1.796	−4.064	−2.294	−3.310
p		.544	.073	**<.001*****	**.022***	**.001**
Impaired sour identification	331	26.4 ± 4.5	2.9 ± 2.8	7.9 ± 3.7	7.4 ± 4.1	18.1 ± 8.8
Intact sour identification	3,821	25.9 ± 4.1	3.1 ± 2.8	8.4 ± 3.3	7.5 ± 3.7	19.0 ± 8.3
t		1.587	−1.221	−3.027	−0.333	−1.849
p		.113	.222	**.002****	.739	.065
Impaired salty identification	106	26.2 ± 4.4	2.8 ± 3.0	7.7 ± 3.6	7.3 ± 4.2	17.6 ± 9.4
Intact salty identification	4,046	25.9 ± 4.1	3.1 ± 2.8	8.4 ± 3.3	7.5 ± 3.7	20.0 ± 8.3
t		0.832	−0.799	−2.116	−0.565	−1.631
p		.405	.424	**.034***	.572	.103

* represents $P < 0.05$, ** represents $P < 0.01$ and *** represents $P < 0.001$.

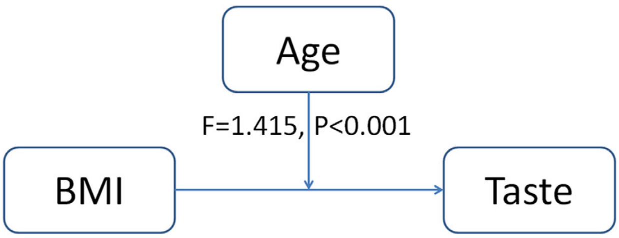

FIGURE 3 Moderating effect of age on the relationship between increased BMI and reduced taste scores. General linear model suggested that BMI*age had a significant effect on taste score

was not shown by the present study. Instead, we found that the relationship between BMI and gustatory function becomes stronger with age. One possible reason is that gustatory dysfunction is more obvious in older people, because the overall number of taste buds and taste cells per taste bud decrease with age (Feng, Huang, & Wang, 2014). Additionally, compared with older people, younger individuals exercise more and have better metabolic function, which may compensate the effect of gustatory dysfunction on weight gain.

5 | LIMITATIONS

First, the present study included subjects from the Smell and Taste Clinic and 91.2% of them exhibited hyposmia or anosmia. Therefore, the present conclusion should be interpreted with caution when generalizing to the population. Second, the utilized Taste Sprays were used for the assessment of sweet, salty, sour and bitter, but not umami. The relationship between BMI and umami needs to be further explored. Furthermore, the Taste Spray score does not reflect gustatory function in its entire granularity, and using Taste Sprays to assess gustation appears not be as comprehensive and robust as using Sniffin' Sticks to assess olfaction. More detailed taste tests, such as the "taste strips" or gustatory event-related potentials may provide a more profound understanding about the relationship between taste and BMI. Third, the present results indicated an association between BMI and chemosensory dysfunction, but their causal relationship needs to be further explored. Forth, obesity is also associated with other reasons independent from chemosensory dysfunction, such as genetic polymorphisms and low physical activity. Future studies including this information could better clarify the relationship between chemosensory dysfunction and obesity. Fifth, different causes of chemosensory dysfunction may affect the relationship with BMI and chemosensory function. Future studies tightly controlling the effects of the etiologies in the statistical analysis could better clarify their relationship. Last, there is an imbalance of sample size in various BMI degrees, which may have affected the statistical analyses. In addition, the obesity class III (BMI > 40) was not included in the present analyses because of its limited sample size.

6 | CONCLUSION

Both obesity class II and an underweight status are associated with gustatory dysfunction, but their patterns were different (obesity class II with impaired bitter identification, underweight with salty identification). Increasing age was associated more strongly with the relationship between gustatory dysfunction and higher BMI, but not with the relationship between olfactory dysfunction and BMI. In summary, these results suggest that taste function is closely related to nutrition conditions. Taste disorders appear to have different effects on body weight dependent on the context.

ACKNOWLEDGMENT

Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

ETHICS STATEMENT

The retrospective study was approved by the Ethics Committee at the "Technische Universität Dresden," Germany (EK 251112006).

ORCID

Ben Chen https://orcid.org/0000-0002-1718-1413
Carla Masala https://orcid.org/0000-0001-5272-8421
Anna Oleszkiewicz https://orcid.org/0000-0003-2217-1858

REFERENCES

Aschenbrenner, K., Hummel, C., Teszmer, K., Krone, F., Ishimaru, T., Seo, H. S., & Hummel, T. (2008). The influence of olfactory loss on dietary behaviors. *Laryngoscope*, *118*, 135–144.

Aschenbrenner, K., Scholze, N., Joraschky, P., & Hummel, T. (2008). Gustatory and olfactory sensitivity in patients with anorexia and bulimia in the course of treatment. *Journal of Psychiatric Research*, *43*, 129–137.

Croy, I., Nordin, S., & Hummel, T. (2014). Olfactory disorders and quality of life—an updated review. *Chemical Senses*, *39*, 185–194.

Dotson, C. D., Shaw, H. L., Mitchell, B. D., Munger, S. D., & Steinle, N. I. (2010). Variation in the gene TAS2R38 is associated with the eating behavior disinhibition in Old Order Amish women. *Appetite*, *54*, 93–99.

Duffy, V. B. (2004). Associations between oral sensation, dietary behaviors and risk of cardiovascular disease (CVD). *Appetite*, *43*, 5–9.

Feeney, E., O'Brien, S., Scannell, A., Markey, A., & Gibney, E. R. (2011). Genetic variation in taste perception: does it have a role in healthy eating?. *Proceedings of the Nutrition Society*, *70*(1), 135–143.

Feng, P., Huang, L., & Wang, H. (2014). Taste bud homeostasis in health, disease, and aging. *Chemical Senses*, *39*, 3–16.

Fernandez-Garcia, J. C., Alcaide, J., Santiago-Fernandez, C., Roca-Rodriguez, M. M., Aguera, Z., Banos, R., … Garrido-Sanchez, L. (2017). An increase in visceral fat is associated with a decrease in the taste and olfactory capacity. *Plos One*, *12*, e0173588.

Fuchida, S., Yamamoto, T., Takiguchi, T., Kandaudahewa, G., Yuyama, N., & Hirata, Y. (2013). Association between underweight and taste sensitivity in middle- to old-aged nursing home residents in Sri Lanka: A cross-sectional study. *Journal of Oral Rehabilitation*, *40*, 854–863.

Gutierrez, R., Fonseca, E., & Simon, S. A. (2020). The neuroscience of sugars in taste, gut-reward, feeding circuits, and obesity. *Cellular and Molecular Life Sciences*, *77*, 3469–3502.

Hardikar, S., Hchenberger, R., Villringer, A., & Ohla, K. (2016). Higher sensitivity to sweet and salty taste in obese compared to lean individuals. *Appetite*, *111*, 158–165.

Hummel, T., Sekinger, B., Wolf, S. R., Pauli, E., & Kobal, G. (1997). Sniffin' sticks': Olfactory performance assessed by the combined testing of odor identification, odor discrimination and olfactory threshold. *Chemical Senses*, *22*, 39–52.

Lim, J., Urban, L., & Green, B. G. (2008). Measures of individual differences in taste and creaminess perception. *Chemical Senses*, *33*(6), 493–501.

McCrickerd, K., & Forde, C. G. (2016). Sensory influences on food intake control: Moving beyond palatability. *Obesity Reviews*, *17*, 18–29.

Naka, A., Riedl, M., Luger, A., Hummel, T., & Mueller, C. A. (2010). Clinical significance of smell and taste disorders in patients with diabetes mellitus. *European Archives of Oto-Rhino-Laryngology*, *267*, 547–550.

Park, D. C., Yeo, J. H., Ryu, I. Y., Kim, S. H., Jung, J., & Yeo, S. G. (2015). Differences in taste detection thresholds between normal-weight and obese young adults. *Acta Oto-Laryngologica*, *135*, 478–483.

Peng, M., Coutts, D., Wang, T., & Cakmak, Y. O. (2019). Systematic review of olfactory shifts related to obesity. *Obesity Reviews*, *20*, 325–338.

Pepino, M. Y., Finkbeiner, S., Beauchamp, G. K., & Mennella, J. A. (2010). Obese women have lower monosodium glutamate taste sensitivity and prefer higher concentrations than do normal-weight women. *Obesity (Silver Spring)*, *18*, 959–965.

Ribeiro, G., & Oliveira-Maia, A. J. (2021). Sweet taste and obesity. *European Journal of Internal Medicine*, *S0953-6205*(21), 00023-6.

Riera, C. E., Tsaousidou, E., Halloran, J., Follett, P., Hahn, O., Pereira, M., … Dillin, A. (2017). The sense of smell impacts metabolic health and obesity. *Cell Metabolism*, *26*, 198–211.e5.

Simchen, U., Koebnick, C., Hoyer, S., Issanchou, S., & Zunft, H. J. (2006). Odour and taste sensitivity is associated with body weight and extent of misreporting of body weight. *European Journal of Clinical Nutrition*, *60*, 698–705.

Skrandies, W., & Zschieschang, R. (2015). Olfactory and gustatory functions and its relation to body weight. *Physiology & Behavior*, *142*, 1–4.

Tsai, A. G., & Bessesen, D. H. (2019). Obesity. *Annals of Internal Medicine*, *170*, ITC33–ITC48.

Turner, A., Veysey, M., Keely, S., Scarlett, C., Lucock, M., & Beckett, E. L. (2018). Interactions between bitter taste, diet and dysbiosis: Consequences for appetite and obesity. *Nutrients*, *10*, 1336.

Vignini, A., Borroni, F., Sabbatinelli, J., Pugnaloni, S., Alia, S., Taus, M., … Fabri, M. (2019). General decrease of taste sensitivity is related to increase of BMI: A simple method to monitor eating behavior. *Disease Markers*, *2019*, 2978026.

Wang, Q., Liszt, K. I., & Depoortere, I. (2020). Extra-oral bitter taste receptors: New targets against obesity? *Peptides*, *127*, 170284.

Welge-Lussen, A., Dorig, P., Wolfensberger, M., Krone, F., & Hummel, T. (2011). A study about the frequency of taste disorders. *Journal of Neurology*, *258*, 386–392.

WHO. (1995). *Physical status: The use and interpretation of anthropometry* (Report of a WHO Expert Committee) (Vol. 854, pp. 1–452). Geneva: Author.

How to cite this article: Chen, B., Masala, C., Oleszkiewicz, A., Englmaier, V., Gunder, N., Menzel, S., Haehner, A., & Hummel, T. (2021). Nonlinear association between chemosensory dysfunction and body mass index. *Journal of Sensory Studies*, e12715. https://doi.org/10.1111/joss.12715