Exploring taste sensitivity variation across different dietary patterns: a cross-sectional study

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Summary
Recent literature suggests that a specific diet can alter taste sensitivities, but little is known about how dietary patterns, excluding whole food groups from the diet (low-carbohydrate, high-fat diets (LCHF), vegan) relate to taste sensitivity. Eighty-two healthy participants were categorized into four groups: omnivore ($n = 22$), vegan ($n = 29$), vegetarian ($n = 17$) and LCHF ($n = 14$). For all participants, detection thresholds (*DT*) for four tastes were determined based on the three-alternative forced-choice method. *K*-means clustering of *DT*s for tastes was performed and the nearest neighbor classifier was applied to predict taste sensitivity in clustering classes. There were differences between dietary patterns, nutrient intakes and biochemical values ($p < 0.05$), but no significant differences in *DT*s for tastes between the dietary pattern groups. Cluster analysis of tasters identified four taste sensitivity profiles. Based on our model, a combination of 30 variables from four categories predicted a person's taste perception cluster with 72% accuracy. Our findings reveal a multifaceted interplay of factors shaping an individual's taste sensitivity. With the exception of vegetarians, participants with other eating habits were in the majority categorized in the cluster of „good taster".

Keywords
taste sensitivity; omnivorous diet; plant-based diet; fat diet; detection threshold

Sensory perceptions, such as taste sensitivities of the five basic taste qualities (sweet, salty, sour, bitter, and umami) and the recently identified fat taste known as "oleogustus" [1] vary widely among individuals. Data regarding the effects of taste sensitivity on food consumption is largely inconclusive [2], but recent literature suggests that diet and taste sensitivity may have a reciprocal relationship, with evidence highlighting that specific diets can alter taste sensitivities [1, 3]. On the other hand, taste perception can influence food choice [4]. The influences on taste sensitivity encompass both internal and external changeable factors [5]. Dietary habits can impact our body composition and biochemical factors, which relate to taste sensitivity. Research shows that people with higher body mass index (*BMI*), visceral fat and fat mass tend to have lower taste sensitivity [6]. Additionally, biochemical parameters such as leptin, triglycerides, HDL cholesterol, glucose and insulin also correlate with taste sensitivity [6]. Studies reveal that the sensitivity and intensity of taste perception change in response to food composition [7–10]. Regular consumption of certain foods can have significant effects on taste sensitivity. For example, a low-sodium diet results in increased salty taste intensity and sensitivity [7]. Similarly, increased sweet taste intensity may be associated with low dietary sugar consumption [8, 9], though findings are contradictory [10].

Various modern diets, which include or exclude different foods and whole food groups, can affect taste perception and food choices [3]. Among mixed diets, there is an increasing trend toward Western diets, particularly in industrialized countries such as the United States and European nations, which is characterized by high consumption of sugar and fat, foods of animal origin and refined carbohydrates [11]. Long-term adherence to such a diet is associated with increased risks

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of chronic diseases, accompanied by altered taste perception [6]. Very high fat intake is also characteristic of the low-carbohydrate, high-fat (LCHF) diet [12]. Although there are no studies investigating the effects of the LCHF diet on taste sensitivity, some studies are investigating high fat intake in relation to taste perception sensitivity thresholds [13]. Not only overnutrition but also nutritional deficiencies lead to changes in taste perception sensitivity. It has been shown that deficiencies in vitamins A, B12, D, and the mineral zinc are associated with atrophy of the lingual papillae and decreased salivary secretion, which can result in reduced taste sensitivity [14]. SCHÜPBACH et al. [15] reported that the intake of these micronutrients was lower in vegans than in omnivorous. Although the number of people following a vegetarian or vegan diet has increased rapidly [3], the number of studies investigating taste perception in the vegan group is limited [3, 14, 16]. Although limited studies exist, most of them suggest no significant differences between plant-based and omnivorous diets, except for bitter taste [3, 14, 16]. However, conflicting data on bitter taste warrant further investigation into potential group differences or methodological influences.

Recent literature suggests that there may be a reciprocal relationship between individual dietary patterns and taste sensitivity [3, 14], but the connection is not clear. Various methods assess taste perception [2–4, 6], and although food is typically a suprathreshold stimulus influencing food choices and linking to dietary patterns, the aim of the present study was to investigate the effects of dietary patterns, particularly the increasingly prevalent plant-based and LCHF diets that exclude whole food groups, on taste sensitivity, measured using the taste detection thresholds (*DT*s). Our additional aims were to develop a data-driven clustering approach to derive taste perception profiles from sweet, salty, bitter, and umami *DT*s and identify which parameters predict the clustering classes.

MATERIALS AND METHODS

Study design and subjects

A cross-sectional study was conducted to determine the taste perception of people with different dietary patterns at the University of Primorska, Faculty of Health Sciences (Slovenia), as a sub-study of a larger study, The Link Between Diets and Health Indicators, that lasted from February 2020 to October 2021. The study protocol was approved by the Slovenian National Medical Ethics Committee (No. 0120-557/2017/4 and 53/03/15) and registered at ClinicalTrials.gov (identifier: NCT04347213). The study protocol was explained to all subjects, and their informed consent was obtained. The study design is shown in Fig. 1.

Subjects were recruited to participate in the

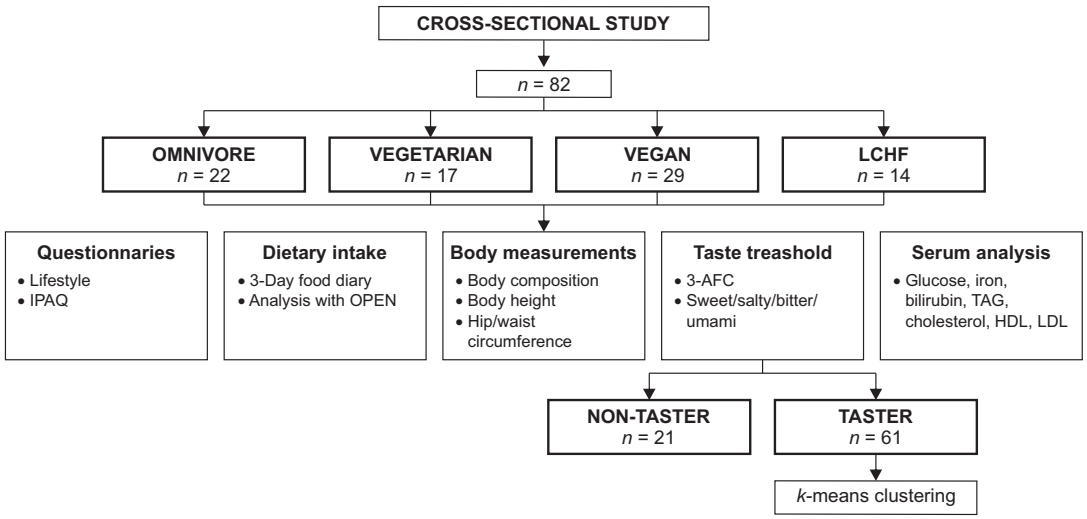

Fig. 1. Study design.

All participants were tested for the four basic tastes. Individuals who did not perceive one or more tastes were defined as non-taster (n = 21).

LCHF – low-carbohydrate, high-fat; IPAQ – International Physical Activity Questionnaire; OPEN – Open Platform for Clinical Nutrition; 3-AFC – three-alternative forced-choice; TAG – triacylglycerol; HDL – high-density lipoprotein; LDL – low-density lipoprotein.

Tab. 1. Concentrations of taste solutions used for threshold testing (ISO 13301 [17]).

Taste	Reference chemical	Concentrations [g·l^{-1}]					
		1	2	3	4	5	6
Sweet	Saccharose	0.34	0.55	0.94	1.56	2.59	12.00
Salty	Sodium chloride	0.16	0.24	0.34	0.48	0.69	2.00
Bitter	Caffeine	0.06	0.07	0.09	0.11	0.14	0.27
Umami	Monosodium glutamate	0.08	0.12	0.17	0.24	0.34	1.00

study through advertising (internet forums, emails and newspaper advertisements). During recruitment, participants were asked about their current dietary pattern and how long they had been following it. Participants who had practised either diet for at least 6 months prior to the study were included in the study [12].

Subjects with mucosal diseases of the tongue (e.g. stomatitis, candidiasis) and/or a history of systemic disease, pregnant and lactating women, subjects with food allergies or intolerances, and subjects who had a medication-induced taste disorder within the last 3 months were excluded from the study. The total sample of the present sub-study included 82 healthy adults.

Determination of taste threshold

Six concentrations of each solution, which were sweet, salty, bitter and umami, were prepared to determine *DT*s. The concentration ranges covered the published thresholds and were adjusted according to the preliminary tests. The concentration ranges (Tab. 1) were set so that the lowest concentration was well below the level at which subjects could detect or recognize the stimulus, and the highest concentration was well above that level.

In each test, participants were given samples at each concentration as an ascending three-alternative forced-choice (3-AFC) series according to International Standards Organization ISO/DIS 13301:2018 [17] as previously described [2]. Starting with the lowest concentration, three samples (10 ml each) per concentration were given to the participants, one containing the chosen concentration of the reference chemical diluted in deionized water, while the other two were background samples (deionized water only). Participants were asked to put the sample in their mouths, swirl the solution, and spit it out. Participants were then instructed to select the sample that was different from the other two. In each set, subjects were asked to identify the different samples; if correct, they were presented with three more samples at the same concentration; if incorrect, they were presented with three more samples at a higher concentration. The testing procedure continued until the subject identified the sample at a given concentration three consecutive times, and that concentration was defined as the subject's *DT*. The participants were asked to rinse their mouths between each new set of samples but not between different samples within the same set.

The individual best estimate threshold (*BET*) for each taste stimulus was calculated as the geometric mean of the highest missed concentration and the next highest correctly detected concentration. If the *DT* was above or below the concentration range used, a hypothetical concentration value was calculated by multiplying or dividing the highest or lowest concentration value by the chosen dilution factor. All *DT*s were within the concentration range chosen for each stimulus.

Assessment of dietary intake

A three-day food diary was used to assess the dietary intake. The participants were asked to include food labels and recipes for mixed dishes whenever possible and to report all dietary supplements taken that day and in general. Portion sizes of foods and meals were quantified in standard units by weight and/or by volume, and photos of the meals were added. Nutrient composition and energy content were analyzed using the web tool Open Platform for Clinical Nutrition (OPEN, University Medical Centre, Ljubljana, Slovenia).

Questionnaires

The online questionnaire consisted of Demographic data, substance use (smoking, alcohol), health status and history, and medication use. We also included questions about hunger and satiety; a detailed description of the questionnaire is presented in Šik Novak et al. [18].

Serum biomarkers

Blood samples were collected in the morning hours after an overnight fast (between 7 and 9 AM). Serum samples were prepared after clot formation by centrifugation at 2 000 ×*g* for 15 min.

Serum aliquots were stored at –80 °C. Serum glucose, triacylglycerol (TAG), total cholesterol, low-density lipoprotein (LDL), high-density lipoprotein (HDL), iron and total bilirubin were measured using Cobas reagents on a Cobas c111 analyzer (Roche, Basel, Switzerland).

Anthropometric measurements

Anthropometric measurements were performed by the same examiner after an overnight fast of at least 12 hours under standardized conditions. Participants' height was measured in the standing position using a stadiometer (Invicta Plastic, Oadby, United Kingdom) with an accuracy of 0.1 cm, while waist and hip circumferences were measured in millimetres using a tape measure. Body weight was measured with Tanita BC 418MA (Tanita, Arlington Heights, Illinois, USA). Body composition was determined by Bodystat Quadscan 4000 multifrequency bioelectrical impedance analysis (BIA) device (Bodystat Douglas, Isle of Man, United Kingdom) in the supine position after a 10-minute rest period.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics, version 26.0 (IBM, Armonk, New York, USA). Shapiro–Wilk test was used to evaluate the normality of data distribution. ANOVA was used to compare groups for normally distributed data, and Kruskall-Wallis' test or Bonferroni post hoc test was used for non-normally distributed data.

Cluster analysis

Clustering analysis of the taste perception sensitivity dataset was performed using an unsupervised technique called *k*-means clustering. Cluster analysis was used to identify distinct subgroups ("clusters") of individuals with similar patterns in *DT*s across four tastes. The *k*-means algorithm clusters data into similar subsets, minimizing the distances within a cluster and maximizing the distance between different clusters. In the present study, the clustering criterion was the sum of squared Euclidean distances between each data point x_i and the centroid m_k (cluster centre) of the subset c_k containing x_i. We used the elbow method to determine the optimal number of clusters.

After the cluster analysis of the taste *DT*s data, we created a model to predict the cluster classes of taste perception sensitivity. We used the *k*-nearest neighbour classifier to build a model and predict the taste perception sensitivity classes based on the variables. The *k*-nearest neighbour classifier finds the *k*-nearest neighbours whose classes are known and assigns the classification label to a new input. In this study, we used cosine distance to calculate the similarities between data points and the 2 nearest neighbours to classify new data points. All 41 features (lifestyle, anthropometric, biochemical parameters, nutritional data) were initially used to build the model. To find important features, the sequential feature selector *sequentialfs* (MATLAB, version: 9.13.0 (R2022b), MathWorks, Natick, Massachusetts, USA) was used to build a subset of features without compromising model accuracy. At each stage, this estimator selects the best feature to add (forward) or remove (backward) based on the cross-validation result. We used the backward search, starting with all 41 variables, and an algorithm sequentially removes features until the criterion decreases. The criterion in this study was classification error. At each step of feature selection, a model is created using the *k*-nearest neighbour method and validated using the leave-one-out procedure. This process is repeated until the criterion (classification error) decreases.

The predictive power of the final model, which includes a subset of selected features, was tested by leave-one-out cross-validation, a special case of *k*-fold cross-validation, where *k* is equal to the number of data points in the dataset. Leave-one-out cross-validation uses the entire dataset to build the model, except for one data point. The prediction is made for a single point that is excluded from the training set. The predicted value is then compared to the true value for validation. The entire process repeats *k* times, where *k* is the number of data points in the dataset.

RESULTS AND DISCUSSION

Subjects characteristics

The present study included 22 omnivores, 17 vegetarians, 29 vegans and 14 participants adhering to the LCHF diet (Fig. 1), who were comparable in terms of gender, fat mass, *BMI* and age. Fifty-nine of the participants were female (72 %) and 23 were male (28 %). Tab. 2 summarizes the anthropometric, biochemical characteristics and nutrient intakes of the different dietary patterns. As expected and confirmed previously [12], there were statistically significant differences in nutritional intakes and serum biochemical parameters between dietary pattern groups. Regarding biochemical parameters, participants adhering to the LCHF diet had significantly higher total (*F*-statistic (*F*) = 9.6, $p < 0.001$, eta-squared (η^2) = 0.33) and LDL cholesterol (*F* = 9.4,

Tab. 2. Anthropometric, biochemical and nutrition variables in participants.

Variables	Omnivore (n = 22)	Vegetarian (n = 17)	Vegan (n = 29)	LCHF (n = 14)	p-value
ANTHROPOMETRIC DATA					
Age (years)	37 ±12	37 ±11	35 ± 12	41 ± 7	0.130
Gender (female/male)	14/8	14/3	21/8	10/4	0.656
Body mass index [kg·m^{-2}]	23 ± 3	21 ± 3	21 ± 2	23 ± 3	0.100
Fat mass [%]	22.6 ± 6.4	23.0 ± 7.8	22.5 ± 7.8	23.1 ± 8.0	0.992
BIOCHEMICAL DATA					
Total cholesterol [mmol·l^{-1}]	4. ± 1.1 ^{c}	4.4 ± 0.7 ^{d}	4.1 ± 0.9 ^{e}	8.9 ± 5.1	< 0.001
LDL [mmol·l^{-1}]	3.1 ± 1.0 ^{c}	2.9 ± 0.7 ^{d}	2.7 ± 0.8 ^{e}	7.4 ± 5.2	< 0.001
HDL [mmol·l^{-1}]	1.9 ± 0.5	1.8 ± 0.4	1.7 ± 0.5 ^{e}	2.1 ± 0.4	0.023
TAG [mmol·l^{-1}]	1.1 ± 0.7	0.7 ± 0.2	0.9 ± 0.4	1.0 ± 0.8	0.535
Glucose [mmol·l^{-1}]	4.9 ± 0.6	4.6 ± 0.4	4.8 ± 0.5	4.6 ± 0.6	0.158
Serum iron [μmol·l^{-1}]	30.1 ± 9.3 ^{c}	16.3 ± 7.3	22.9 ± 10.4	17.6 ± 6.2	< 0.001
NUTRITION DATA					
Energy intake [kJ·d^{-1}]	9 005 ± 3 032	8 417 ± 2 885	8 589 ± 1 907	8 371 ± 2 759	0.774
Proteins intake [g·d^{-1}]	96 ± 48 ^{ab}	62 ± 26 ^{d}	62 ± 17 ^{e}	112 ± 42	< 0.001
Carbohydrates intake [g·d^{-1}]	248 ± 103 ^{c}	253 ± 122 ^{d}	303 ± 106 ^{e}	45 ± 41	< 0.001
Sugar [g·d^{-1}]	88 ± 45 ^{c}	85 ± 53 ^{d}	99 ± 52 ^{e}	27 ± 29	< 0.001
Fat intake [g·d^{-1}]	79 ± 25 ^{c}	81 ± 24 ^{d}	61 ± 22 ^{e}	149 ± 55	< 0.001
Fibre [g·d^{-1}]	26 ± 23 ^{b}	34 ± 17 ^{d}	44 ± 19 ^{e}	19 ± 27	< 0.001
Vitamin B12 [μg·d^{-1}]	5 ± 3 ^{b}	212 ± 696	261 ± 954 ^{e}	11 ± 13	< 0.001
Vitamin D [μg·d^{-1}]	6 ± 8	39 ± 138	15 ± 21	11 ± 9	0.073
Vitamin A [μg·d^{-1}]	2 028 ± 6 125	1 175 ± 1 782	1 119 ± 770	1 208 ± 907	0.218
Zinc [mg·d^{-1}]	11 ± 4	13 ± 9	9 ± 5	13 ± 5	0.096
Sodium [mg·d^{-1}]	2 861 ± 1 163	2 602 ± 2 307	2 267 ± 1 117	3 036 ± 2 366	0.254

The results are given as the mean ± standard deviation. Significant differences between a pair of groups ($p < 0.05$) are indicated in the superscript index as follows: a – omnivore/vegetarian, b – omnivore/vegan, c – omnivore/low-carbohydrate, high-fat diet, d – vegetarian/low-carbohydrate, high-fat diet, e – vegan/low-carbohydrate, high-fat diet.
LCHF – low-carbohydrate, high-fat diet, LDL – low-density lipoprotein, HDL – high-density lipoprotein, TAG – triacylglycerol.

$p < 0.001$, $\eta^2 = 0.33$) than participants in all other groups. Additionally, a one-way ANOVA revealed a significant and large effect of the dietary pattern on HDL cholesterol ($F = 1.4$, $p = 0.023$, $\eta^2 = 0.07$) and serum iron levels ($F = 5.4$, $p < 0.001$, $\eta^2 = 0.22$). Indeed, omnivores had significantly higher serum iron levels than vegetarians, and participants in LCHF group had significantly higher serum levels of HDL cholesterol than vegans. Regarding nutrition, significant differences between the LCHF group and all other groups were found in carbohydrates ($F = 14.74$, $p < 0.001$, $\eta^2 = 0.43$), sugar ($F = 5.8$, $p < 0.001$, $\eta^2 = 0.23$) and fat intake ($F = 10.5$, $p < 0.001$, $\eta^2 = 0.35$). There were also significant differences between the groups in protein ($F = 4.7$, $p = 0.002$, $\eta^2 = 0.20$), fibre ($F = 5.0$, $p < 0.001$, $\eta^2 = 0.21$) and B12 intake ($F = 1.3$, $p < 0.001$, $\eta^2 = 0.06$). Indeed, vegans and vegetarians had significantly lower intakes of protein and higher intakes of fibre than participants in the omnivorous and LCHF groups. Because of vitamin B12 supplementation, especially in the vegan and vegetarian groups, vegans had a significantly higher intake of vitamin B12 than participants in the omnivorous and LCHF groups.

Prevalence of non-tasters among participants

Tab. 3 reports the mean values of *DT*s to each of the testing compounds derived from the separate groups. After determining taste sensitivity, we found that about 25 % of people were non-tasters because they did not perceive one or more tastes (and do not refer to the phenylthiocarbamide/6-*n*-propylthiouracil (PTC/PROP) phenotype). Individuals belonging to the non-taster group reported the least favourable perception of all taste modalities. Specifically, a subset of 17 indivi-

duals within this group did not perceive the bitter taste, 6 were unable to detect the umami taste, and one subject failed to perceive the salty taste. Overall, non-tasters had significantly higher *DT*s for all tastes than tasters. Our results are in line with expectations and consistent with the results of other studies that had a similar percentage of non-tasters, primarily stemming from the inability to perceive bitter and umami tastes. O'Brien et al. [4] demonstrated that 28 % of subjects had low PROP scores and were classified as non-tasters. Although we used caffeine to assess bitter taste perception in our study, we found that 21 % of individuals did not perceive it. It is recognized that about 30 % of the population does not perceive the bitter taste [19]. Similarly, regarding umami perception, Wu et al. [20] showed in a literature review that 3.5–4.6 % of individuals do not perceive umami, while in our case, 5 % of participants did not perceive umami. It is known that a plant-based diet could influence the perception of bitter taste [21], but the influence of genetic background [4] and microbiota should not be neglected either [22].

Participants of all dietary patterns were classified as non-tasters, as follows: 41.1 % of vegetarian participants, 24.0 % of omnivores, 22.7 % of vegans and 14.3 % of LCHF participants. Reduced perception of taste in the non-taster group might pose a health risk, as studies show that non-tasters choose less healthy foods and have unhealthy lifestyles [1]. Previous studies have shown that non-tasters have high energy intake [1], but in our case the non-taster group tended to have lower energy, macro- and micronutrient intakes than tasters, but significant differences between non-taster and taster groups were observed only in intakes of vitamin B12 (11 ± 6 $\mu g \cdot d^{-1}$ vs 183 ± 751 $\mu g \cdot d^{-1}$ respectively, $p = 0.037$) and zinc (9 ± 6 $mg \cdot d^{-1}$ vs 12 ± 6 $mg \cdot d^{-1}$ respectively, $p = 0.041$). Both microelements are known to influence taste sensitivity, especially salty taste [23]. It is known that zinc is important for the functioning of taste buds [24]. Disturbance of salivary zinc levels has been found to be associated with a decreased level of gustin [25], the major zinc-containing protein in the human parotid saliva. A decrease in the secretion of gustin has been linked to abnormalities in the growth and development of the taste buds and the resultant loss of taste [26]. We also observed a negative correlation between *DT* for salty and fibre intake ($r = -0.549$, $p = 0.012$) in non-tasters. Dietary fibre may influence taste changes as a prebiotic, in part by maintaining a healthy gut microbiota. In the past, it has been suggested that the gastrointestinal microbiota influences host eating behaviour and affects food preferences [27]. When gut health was not maintained, sensitivity to salty taste decreased [28].

Taste sensitivity across different dietary patterns

Tasters were subdivided according to their dietary patterns. In tasters, we could not observe any differences in taste *DT*s between different

Tab. 3. Comparison of the tested detection thresholds taste between non-taster and taster groups.

Taste	Detection threshold [$g \cdot l^{-1}$]		*F*-value	*p*-value
	Non-taster ($n = 21$)	Taster ($n = 61$)		
Salty	0.75 ± 0.60	0.32 ± 0.20	23.6	< 0.001*
Sweet	3.40 ± 2.37	1.71 ± 1.89	10.8	0.002*
Bitter	0.27 ± 0.08	0.09 ± 0.04	184.7	< 0.001*
Umami	0.48 ± 0.49	0.18 ± 0.12	19.3	< 0.001*

The results are given as the mean ± standard deviation. * – significant differences between the non-taster and taster group ($p < 0.05$).

Tab. 4. Comparison of the tested detection thresholds taste between tasters according to the dietary pattern.

Taste	Detection threshold [$g \cdot l^{-1}$]				*F*-value	*p*-value
	Omnivore ($n = 17$)	Vegetarian ($n = 10$)	Vegan ($n = 22$)	LCHF ($n = 12$)		
Salty	0.31 ± 0.25	0.39 ± 0.30	0.32 ± 0.14	0.27 ± 0.09	0.660	0.579
Sweet	1.15 ± 1.29	2.11 ± 1.88	1.60 ± 1.95	2.36 ± 1.42	1.135	0.343
Bitter	0.08 ± 0.03	0.09 ± 0.03	0.09 ± 0.04	0.10 ± 0.06	0.771	0.515
Umami	0.17 ± 0.12	0.22 ± 0.14	0.14 ± 0.07	0.21 ± 0.18	1.190	0.322

The results are given as the mean ± standard deviation. LCHF— low-carbohydrate, high-fat diet.

Tab. 5. Detection thresholds and proportion of subjects according to the dietary pattern in the four clusters.

Taste	Detection threshold [g·l^{-1}]				*F*-value	*p*-value
	C1 (n = 10)	C2 (n = 27)	C3 (n = 9)	C4 (n = 15)		
Salty	0.24 ± 0.11 ^{c}	0.22 ± 0.06 ^{de}	0.37 ± 0.14	0.51 ± 0.29	10.51	< 0.001
Sweet	1.17 ± 1.58 ^{b}	0.89 ± 0.58 ^{d}	5.57 ± 0.10 ^{f}	1.23 ± 1.36	52.84	< 0.001
Bitter	0.09 ± 0.05	0.09 ± 0.04	0.10 ± 0.05	0.07 ± 0.02	1.32	0.274
Umami	0.37 ± 0.18 ^{abc}	0.13 ± 0.06	0.12 ± 0.07	0.15 ± 0.05	17.51	< 0.001

Detection threshold for each taste is given as the mean ± standard deviation.
C1 – cluster 1 (high umami detection threshold), C2 – cluster 2 (good taster), C3 – cluster 3 (low umami and high sweet detection threshold), C4 – cluster 4 (low bitter and high salty detection threshold).
Significant differences between a pair of clusters (p < 0.001) are indicated in the superscript index as follows: a – C1/C2; b – C1/C3; c – C1/C4; d – C2/C3; e – C2/C4; f – C3/C4.

Tab. 6. Representatives of subjects according to the dietary pattern in the four clusters.

Diet	Participants	C1 (n = 10)	C2 (n = 27)	C3 (n = 9)	C4 (n = 15)	Total
LCHF	[%]	16.7	50.0	25.0	8.3	100
	n	2	6	3	1	12
Vegan	[%]	4.5	50.0	18.2	27.3	100
	n	1	11	4	6	22
Vegetarian	[%]	40.0	20.0	10.0	30.0	100
	n	4	2	1	3	10
Omnivore	[%]	17.6	47.0	5.9	29.4	100
	n	3	8	1	5	17

C1 – cluster 1 (high umami detection threshold), C2 – cluster 2 (good taster), C3 – cluster 3 (low umami and high sweet detection threshold), C4 – cluster 4 (low bitter and high salty detection threshold).
LCHF – low-carbohydrate, high-fat diet.

diet groups (Tab. 4), which is in agreement with Nuvoli et al. [16], whereas some studies show differences, especially in the taste sensitivity for bitter and fatty tastes [21].

Cluster analysis

Because no significant differences in *DT*s for tastes between dietary pattern groups were observed, we were additionally interested in whether clustering based on *DT*s for sweet, salty, bitter and umami tastes could be related to dietary pattern or to a specific dietary intake or nutritional status. Hierarchical clustering revealed an elbow at $k = 4$, suggesting that the dataset (taster group) can be organized into four clusters.

In Tab. 5, specific characteristics of each cluster are shown. A one-way ANOVA revealed a significant and large effect of the clusters on salty *DT* ($F = 10.5$, $p < 0.001$, $\eta^2 = 0.36$), sweet *DT* ($F = 52.8$, $p < 0.001$, $\eta^2 = 0.74$), and umami *DT* ($F = 17.5$, $p < 0.001$, $\eta^2 = 0.48$).

Cluster 1 (labelled C1, high umami detection threshold, $n = 10$) is characterized by low umami taste sensitivity, significantly lower than in all other clusters ($p < 0.001$). Cluster 2 (C2, good taster, $n = 27$) is numerically the largest cluster and is characterized by a high sensitivity for all tastes. Participants in cluster 3 (C3, low umami and high sweet detection threshold, $n = 9$) had a statistically lower sweet taste sensitivity compared to all other clusters ($p < 0.001$), but on the other hand, they had a higher umami taste sensitivity. Cluster 4 (C4, low bitter and high salty detection threshold, $n = 15$) is characterized by high bitter taste sensitivity and low salty taste sensitivity, significantly different in comparison to C1 ($p < 0.001$). In C2, significantly lower *DT* for salty and sweet was observed than in C3 and C4 ($p < 0.001$).

Representatives of all dietary patterns were found in all clusters. Approximately half of vegans, omnivores, and LCHF were included in the "good taster" cluster (C2), while there were only one-fifth of vegetarians (Tab. 6). The highest percentage of vegetarians (40 %) was detected in cluster C1 (Tab. 6).

Classification models and predictors

We were additionally interested in which fea-

tures predict the classification of participants into clusters. The sequential feature selector removed 11 features so that 30 features (Tab. 7) were included in the final model. The accuracy of the final model was 72 %. The classification of participants in C2 and C4 clusters achieved accuracy of 85.2 % and 80.0 %, respectively, while the classification of participants in clusters C1 and C3 was less accurate (Tab. 8).

The most important predictors of *DT*s for tastes came from the following categories: anthropometric measurements, serum biomarkers, lifestyle factors and intake of certain nutrients. In accordance with previous research [5], gender was a significant predictor of taste sensitivity. Additionally, we observed that body composition affected taste sensitivity, as the cluster analysis included five predictive factors from this category at once (*BMI*, fat mass, waist-hip ratio, visceral fat and total body water). The results also agree with other published studies showing that body composition can influence taste perception sensitivity [6]. Moreover, previous studies have shown that taste sensitivity is related to biochemical factors [1, 29], and we confirmed that serum levels of LDL and HDL cholesterol, glucose, iron and bilirubin were important predictors of taste sensitivity. The values of these predictors are reported in Tab. 9 for each cluster.

The majority of tasters were classified in cluster C2, a good taster. 50 % of LCHF participants, 50 % of vegans, 47 % of omnivores and 20 % of vegetarians were clustered here. Participants in C2, who perceived all tastes well, had the highest protein intake (92 ± 39 g·d^{-1}, $p = 0.044$) and a recognizable preference for the palatability of food (4.5 ± 0.7 scores, $p = 0.045$), which was statistically different from participants in C4 (70 ± 29 g·d^{-1}, 4.0 ± 0.8 scores respectively). In cluster C4, 30 % of vegans, 27 % of vegetarians and 29 % of omnivores were classified. Interestingly, we observed that in C4, there was the lowest number of people following a LCHF diet (8.3 %). The cluster is characterized by a poor perception of salty taste and a good perception of bitter taste. Participants of this cluster had the lowest protein intake, and some authors suggested that a diet with low protein intake contributed to an imbalanced amino acid intake, which could influence the thresholds for salty taste perception and salt intake [7]. However, a newer study has not shown that protein intake influenced the

Tab. 7. Predictors of taste sensitivity for classification model.

Predictors			
Anthropometrics and gender parameters	Biochemical parameters	Nutritional data	Other parameters
Gender Waist circumference Body fat mass Visceral fat Total body water	LDL cholesterol HDL cholesterol Iron in serum Total bilirubin Fasting glucose	Energy intake Protein intake Carbohydrates intake Fat and cholesterol intake Fibre intake Vitamin A, D and B12 intake Intakes of Zn, Ca, Na Alcohol intake/frequency of consumption ORAC value	Appetite for sweet foods Appetite in general Smoking habits, smoking years Taste of food

LDL – low-density lipoprotein, HDL – high-density lipoprotein, ORAC – oxygen radical absorbance capacity.

Tab. 8. The confusion matrix of the *k*-nearest neighbour classifier model.

		Predicted class					
		1	2	3	4		
True class	1	**4**	3		3	**40.0 %**	60.0 %
	2		**23**	1	3	**85.2 %**	14.8 %
	3		4	**5**		**55.6 %**	44.4 %
	4		3		**12**	**80.0 %**	20.0 %
		100 %	**69.7 %**	**83.3 %**	**66.7 %**		
			33.3 %	16.7 %	33.3 %		

The confusion matrix of the *k*-nearest neighbour classifier model where 30 predictors were included (72% accuracy; true predictions and accuracy are marked in bold).

Tab. 9. Anthropometric, biochemical and nutrition variables in clusters.

Variables	C1 (n = 10)	C2 (n = 27)	C3 (n = 9)	C4 (n = 15)
ANTHROPOMETRIC DATA				
Gender (female/male)	7/3	17/10	7/2	12/3
Fat mass [%]	24.1 ± 6.9	21.6 ± 8.2	23.7 ± 6.4	22.4 ± 7.3
Visceral fat rating	5.1 ± 2.7	3.5 ± 2.3	3.8 ± 3.0	2.6 ± 2.2
Total body water [%]	53.7 ± 4.6	56.4 ± 6.8	54.5 ± 4.9	55.5 ± 5.1
Waist circumference [cm]	79.5 ± 7.6	76.3 ± 9.3	77.0 ± 13.0	73.6 ± 7.6
SERUM BIOMARKERS				
LDL [mmol·l^{-1}]	4.2 ± 3.1	4.3 ± 4.1	2.9 ± 0.6	3.2 ± 1.6
HDL [mmol·l^{-1}]	1.7 ± 0.5	2.0 ± 0.4	1.8 ± 0.5	1.8 ± 0.5
Glucose [mmol·l^{-1}]	4.8 ± 0.6	4.8 ± 0.4	4.8 ± 0.7	4.7 ± 0.6
Iron [μmol·l^{-1}]	20.3 ± 11.0	24.0 ± 11.2	23.9 ± 10.0	23.0 ± 11.7
Bilirubin [μmol·l^{-1}]	7.3 ± 3.4	9.8 ± 7.8	10.3 ± 4.6	9.0 ± 6.0
NUTRITIONAL INTAKE				
Energy [kJ·d^{-1}]	8 555 ± 2 007	9 387 ± 3 062	8 144 ± 1 743	8 747 ± 2 667
Protein [g·d^{-1}]	73 ± 33	92 ± 39 [b]	80 ± 48	70 ± 29
Carbohydrates [g·d^{-1}]	217 ± 98	258 ± 169	206 ± 124	254 ± 136
Fat [g·d^{-1}]	95 ± 31	90 ± 48	86 ± 43	79 ± 33
Cholesterol [g·d^{-1}]	389 ± 494	367 ± 460	306 ± 436	226 ± 340
Fibre [g·d^{-1}]	31 ± 16	35 ± 24	31 ± 22	36 ± 27
Vitamin B12 [μg·d^{-1}]	3 ± 3	100 ± 286	4 ± 5	561 ± 1435
Vitamin D [μg·d^{-1}]	6 ± 8 [a]	12 ± 13	13 ± 19	41 ± 147
Vitamin A [μg·d^{-1}]	776 ± 406	931 ± 734	4 226 ± 9 457	1 071 ± 918
Zinc [mg·d^{-1}]	11 ± 8	12 ± 5	12 ± 8	11 ± 7
Sodium [g·d^{-1}]	2.7 ± 2.7	3.0 ± 1.8	2.1 ± 1.2	2.3 ± 1.1
Calcium [mg·d^{-1}]	1 487 ± 2 255	849 ± 390	790 ± 740	1 201 ± 1 083
ORAC [mmol·kg^{-1}]	12 137 ± 8 083	9 172 ± 5 200	12 493 ± 10 651	10 150 ± 11 840
Alcohol intake (units per week)	1.2 ± 1.9	2.0 ± 3.7	2.8 ± 4.9	0.7 ± 1.4
LIFESTYLE				
Active smokers [%]	10	14.8	22.2	13.3
No smokers [%]	90	85.2	77.8	86.7
Smoking [years]	0.4 ± 1.2	3.4 ± 8.9	2.7 ± 6.6	1.2 ± 3.1
Taste of food (score 1–5)	4.3 ± 0.5	4.5 ± 0.7 [b]	4.5 ± 0.5	4.0 ± 0.8
Appetite for sweet food (score 1–10)	5.3 ± 2.9	4.21 ± 3.0	5.2 ± 3.4	4.9 ± 2.2
Appetite the week preceding measurement (score 1–5)	3.9 ± 0.7	4.0 ± 0.8	4.0 ± 1.1	3.6 ± 0.6

The results are given as the mean ± standard deviation.
C1 – cluster 1 (high umami detection threshold), C2 – cluster 2 (good taster), C3 – cluster 3 (low umami and high sweet detection threshold), C4 – cluster 4 (low bitter and high salty detection threshold).
Significant differences between a pair of clusters ($p < 0.05$) are indicated in the superscript index as follows: a – C1/C4; b – C2/C4.
LDL – low-density lipoprotein, HDL – high-density lipoprotein, *ORAC* – oxygen radical absorbance capacity (expressed as millimoles of Trolox equivalents per kilogram of food).
Alcohol intake is expressed as units per week, where one unit corresponds to 10 ml of pure alcohol.
Taste food and appetite (score 1–5): 1 – very poor, 5 – very good.
Appetite for sweet food (score 1–10): 1 – no appetite at all, 10 – very strong appetite.

threshold for salty taste perception [30]. We have to point out that protein intake was not the only predictor for clustering. Instead, our study points to a multifaceted interplay of factors shaping an individual's taste sensitivity. A good perception of bitter taste, also characteristic of C4, was associated with lower alcohol consumption [3], and indeed, participants in C4 had the lowest alcohol consumption (0.7 ± 1.4 units per week). We have also shown certain vitamins and minerals to be important predictors of taste perception, which is also confirmed by other studies [23, 24]. C4 was characterized by a high intake of vitamin B12 ($561 \pm 1\,435$ $\mu g \cdot d^{-1}$), well above the lower recommended limit of 4 $\mu g \cdot d^{-1}$, and was the only group that met the recommendations for vitamin D intake (41 ± 147 $\mu g \cdot d^{-1}$, recommendation 20 $\mu g \cdot d^{-1}$). Vitamin D intake (6 ± 8 $\mu g \cdot d^{-1}$) in C1 was statistically lower than in C4 ($p < 0.05$). Intake of vitamin A in C3 ($4\,225 \pm 9\,457$ $\mu g \cdot d^{-1}$) exceeded tolerable upper intake levels (3 000 $\mu g \cdot d^{-1}$) [31].

Although a large proportion of vegetarians was included in the non-taster group, a trend of poorer taste sensitivity was observed for the rest of the vegetarian group compared to participants adhering to other diets (Tab. 6). 40 % of vegetarian tasters were found in C1, where the lowest umami taste sensitivity was observed. The literature reports that umami taste perception is particularly related to protein intake [31]. Protein intake in C1 did not differ significantly from clusters with better umami taste sensitivity. Besides protein intake, we identified many other predictors of taste sensitivity, which was also confirmed by other researchers in the case of umami taste [16, 32].

In the last ten years, a diet that excludes carbohydrates and is based on a high fat intake has also become increasingly popular. Although participants adhering to the LCHF diet tended to have lower sensitivity for sweet taste, no significant differences between dietary pattern groups regarding taste perception were observed. Moreover, after further cluster analysis, we found that the majority (50 %) of subjects adhering to the LCHF diet were classified into a group with good taste perception (C2). The smallest number of participants was classified into the C3 cluster, showing poor taste sensitivity for sweet and a good taste sensitivity for umami. A quarter of participants adhering to LCHF dietary pattern were in this cluster, which is interesting, as participants adhering to LCHF consume only small amounts of sugar and other carbohydrates in their diet. No studies describing the *DT*s of taste sensitivity for participants adhering to LCHF dietary pattern were found.

CONCLUSION

This study underscores the intricate relationship between dietary patterns and taste perception sensitivity. Our findings indicate that dietary patterns are not the primary predictors of *DT*s and, on the sensitivity, can be influenced by many factors, from endogenous factors (gender, body composition and biochemical parameters) to exogenous factors (macro- and micronutrient intake). It is worth noting that we did not find differences in taste perception among dietary patterns groups, but we did show that a quarter of the participants were non-taster, with a significant portion of them following a vegetarian diet. The integration of these findings into the food industry, health recommendations, and consumer behaviour strategies holds the potential for significant positive impacts on public health and consumer satisfaction.

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