# Cross-cultural differences in lingual tactile acuity, taste sensitivity phenotypical markers, and preferred oral processing behaviors

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**Abstract**

Cultural and genetic differences in consumer populations across the world are important determinants for food preferences. The present study investigated differences in preferred oral processing behaviors between Chinese Asian and Danish Caucasian consumers and the possible relationship to lingual tactile acuity and the two most well-researched phenotypic markers of taste sensitivity, such as 6-n-propylthiouracil (PROP) responsiveness and Fungiform Papillae Density (FPD).

A total of 152 consumers (75 Chinese, 77 Danish) were enrolled in the study and categorized by their preferred oral processing behaviors. Lingual tactile acuity was assessed according to responses to stimulation with Von Frey filaments. The responsiveness to PROP and the FPD were also determined. Cross-population differences were found in preferred food oral processing behaviors in these two cohorts, as Chinese consumers were characterized by a larger number of 'Soft processing likers' (77% of the population) who preferred soft food processing in the mouth. Contrarily, Danish consumers mostly belonged to the 'Firm processing likers' group (73% of the population) who had preferences for foods that needed firm processing on biting and chewing. Moreover, the group of 'Firm processing likers' were shown to be more sensitive than the 'Soft processing likers' in both population cohorts. Cross-population differences in lingual tactile acuity were not significant. Differences in FPD and PROP responsiveness were found between these two population cohorts, with Chinese consumers generally characterized by greater FPD and PROP responsiveness compared to the Danish subjects.

This study provides evidence on cross-cultural differences in preferred oral processing behaviors and in the two phenotypic marker of taste sensitivity. However, further studies are needed to draw conclusive relationships between preferred oral processing behavior and oral tactile acuity, PROP responsiveness and tongue anatomy.

52 **1. Introduction**

53 The variation in oral texture perception of foods across consumer populations is supposed to depend
54 on individual differences in tactile acuity and processing behaviors in the mouth. Tactile acuity has
55 been widely studied at the surface of the skin (for a review: Abraira & Ginty, 2013) and four
56 mechanoreceptors have been identified. These specialized nerve endings convey specific sensations
57 such as light pressure and touch as well as stretch and high-frequency vibration. In the anterior tongue,
58 neuroanatomical studies have shown that somatosensory trigeminal neurons terminate as a network
59 of fibers in the peri-gemmal tissue (des Gachons et al., 2011; Suemune et al. 1992; Whitehead,
60 Beeman, & Kinsella, 1985). Gairns and Garven (1952) were the first to find anatomical evidence in
61 humans that somatosensory endings from the trigeminal nerve (V) innervate Fungiform Papillae (FP).
62 Later research confirmed these findings and showed that twenty-five percent of FP innervation arise
63 from the chorda tympani nerve (taste), and seventy-five percent from the trigeminal nerve (pain, touch
64 and temperature) (Silver & Finger, 1991). Mechanical stimuli are likely to activate some receptors of
65 the trigeminal nerve endings, which surround taste buds in the FP and terminate in the papilla apex
66 (des Gachons et al., 2011). Considering FP as a common anatomical unit of the sense of taste and the
67 somatosensory system, these anatomical structures are assumed to act as an 'array of sensors for
68 detecting oral touch sensations' (Bartoshuk et al. 1994; Prescott, Soo, Campbell, & Roberts, 2004;
69 Prutkin et al., 2000) and predict tactile acuity and discrimination (Bangcuyo & Simons, 2017;
70 Engelen & Van der Bilt, 2008; Prescott, Soo, Campbell, & Roberts, 2004). This anatomical colocation
71 can explain the positive correlations between FP and trigeminally mediated oral somatosensations
72 such as the tongue spatial resolution acuity (Bangcuyo & Simons, 2017; Essick, Chopra, Guest, &
73 McGlone, 2003), the textural aspects of creaminess (Hayes & Duffy, 2007; 2008; Nachtsheim &
74 Schlich, 2013; Proserpio et al., 2016) and roughness perception (Bakke & Vickers, 2008).
75 In addition to the relationship between FP and lingual tactile acuity the responsiveness to the bitter
76 tastant 6-n-propylthiouracil (PROP) has also been proposed has another factor involved in texture
77 perception. Indeed, several studies have associated PROP taster status with the perceived intensity
78 and the ability to discriminate trigeminal sensations and textures (Bakke & Vickers, 2011; Bartoshuk
79 et al., 1994; de Wijk et al., 2007; Pickering, Simunkova, & Di Battista, 2004; Pickering & Robert,
80 2006; Tepper & Nurse, 1997; Yackinous & Guinard, 2001). However, results on association between
81 PROP status and texture are still contradictory and some studies could not find associations between
82 PROP status and oral texture perception (Drewnowski et al. 1998; Lim, Urban, & Green, 2008).
83 There are some indications that Asian and Caucasian consumers have different oral chemosensory
84 abilities (Guo & Reed, 2001; Tepper, 2008). In Caucasian populations, 20 to 25% is estimated to be
85 PROP non-taster (less responsive to PROP). Whereas the estimated proportion of non-tasters in Asian

populations in China and Japan is between 10 and 20% (Guo & Reed, 2001). Additionally, Essick and colleagues (2003) found that PROP sensitivity seems to covary among Asian and Caucasian females, reflecting individual differences in the density and diameter of FP on the anterior tongue. However, very few studies investigated possible ethnicity differences in food texture perception and no differences in oral tactile acuity between Caucasian and Asian subjects could be detected by the letter recognition method (Essick, Chopra, Guest, & McGlone, 2003).

This letter recognition method has been popular for measuring oral touch sensitivity across subjects (Essick, Chen, & Kelly, 1999; Essick, Chopra, Guest, & McGlone 2003; Lukasewycz & Mennella 2012; Steele, Hill, Stokely, & Peladeau-Pigeon, 2014). In this test subjects are asked to use their tongues to identify letters of the alphabet of varying sizes embossed onto Teflon strips (Essick et al., 1999). A challenge with the oral letter test is that subjects across cultures may differ in their recognition ability due to different alphabets and symbols in their languages, thus making this method possibly less suitable for cross-cultural studies. Other methods for oral touch acuity include a two-point discrimination task (Engelen, Van der Bilt, & Bosman, 2004), grating orientation discrimination (Van Boven & Johnson, 1994), and other physiological measures (Bangcuyo & Simons, 2017; Linne & Simons, 2017). The majority of studies on oral tactile acuity utilized static or moving two-point discrimination or grating recognition tasks, which may have limited reliability as tools for determining touch detection and punctate pressure (Miles et al., 2018). An alternative method concerns a localized one point touch testing with von Frey fibers (Semmes-Weinstein monofilaments). This method concerns a touch detection task, where subjects report presence or absence of the stimulus. This method is reported to be repeatable, accurate, and most reliable for measuring light touch–deep pressure sensibility of the tongue and the hard palate (Bell-Krotoski & Tomancik, 1987; Bodin, Jäghagen, & Isberg, 2004; Cordeiro, Schwartz, Neves, & Tuma, 1997; Henkin & Banks, 1967). When studying cross-cultural differences in oral touch acuity, methods aiming at point touch detection may be more suitable as they provide localized absolute detection thresholds. Thus preventing biases from cultural differences in object recognition.

Besides the phenotypic markers of taste sensitivity and lingual tactile acuity, there is a growing body of research on oral processing behavior, i.e. the way to manipulate and manage a food in the mouth (de Wijk, van Gemert, Terpstra, & Wilkinson, 2003; Jeltema, Beckley, & Vahalik 2014; 2015; 2016; Yackinous & Guinard, 2001). It has been suggested that differences in food manipulation and mastication could affect sensory sensations (Lassauzay et al., 2000; Po et al., 2011). Brown and Braxton (2000) identified four different groups of people based on their efficiency in reducing the size of foods (i.e. almonds and chewing gum) and suggested that individual differences in the mouth ability to manipulate and handle the product may be an important driver of liking and preferences.

More recently, Jeltema and collaborators (2014) suggested the existence of Mouth Behavior (MB) groups and showed that consumers can be typified by the way they manipulate food in their mouths. Their scheme categorized consumers into so-called (a) Smooshers, (b) Suckers, (c) Chewers, and (d) Crunchers. These groups fell into two major mouth processing styles. The first one, represented by Suckers and Smooshers, preferred to process food between the mouth's roof and tongue. They diverged principally in the hardness of preferred foods. Suckers preferred harder foods that could be sucked on for a long time, such hard candies and foods that they could hold in their mouths. Smooshers preferred soft foods, such as puddings or creamy candies that would spread throughout the mouth and could be held in for a longer time, not requiring much mouth activity. The second one, represented by Crunchers and Chewers, preferred to use their teeth to break down foods. In particular, Crunchers were more forceful in their bite, preferring foods that broke up on biting. Chewers liked foods that did not fracture on biting and could be chewed. If such consumer MB groups exist, one would expect a possible cultural dimension, as different populations have different habits on how to prepare and consume foods. However, such differences in oral MB may also be related to fundamental differences in mouth anatomy and texture perception. Moreover, other factors such as salivary flow, mouth size, dental bite, dental status and health could play a role in defining subjects' MB, affecting chewing and mastication performance (Chen, 2009; Jeltema, Beckley, & Vahalik, 2016).

Thus, there are evidences to suggest that PROP phenotypical and population cultural factors may play a role in texture perception and preferences. PROP tasters appear to have a better lingual tactile acuity than other taster groups and may more readily detect small particles and granularity in foods. It seems plausible that PROP tasters will be more sensitive to gritty contaminants in foods and may more readily reject such foods (Essick, Chopra, Guest, & McGlone, 2003). Thus, a high responsiveness to PROP and variation in FPD are possibly involved in choices of some food textures. Likewise, other influences such as personality traits, cultural habits and societal factors are most certainly important in texture preferences. As reported above, it has well been established that Asian and Caucasian populations differ in PROP responsiveness, which is most definitely seen in the higher proportion of supertaster-tasters in the Asian population. It is less certain that Asian and Caucasian populations differ in lingual tactile acuity beyond differences in their PROP status and FPD counts. The two populations have not been shown to differ in the letter recognition task on the anterior dorsal part of the tongue, but no studies have reported differences on touch detection ability on this part of the tongue.

The present study aimed at investigating whether differences exist in PROP responsiveness, FPD and touch detection ability on the anterior dorsal part of the tongue among Asian and Caucasian adults. Furthermore, the importance of such sensory differences for preferred oral food processing behaviors

154 in these populations has been explored. The objectives were to (i) find relationships between PROP
155 taste sensitivity, FPD and touch detection ability among Asian and Caucasian population cohorts, (ii)
156 classify Asian and Caucasian according to their preferred food oral processing behaviors, and (iii)
157 explore lingual touch detection ability in relation to oral texture preferences.
158

159 **2. Material and methods**

160 *2.1 Subjects*

161 One hundred and fifty-two healthy, non-smoking subjects between the ages of 18 and 55 years were
162 recruited to attend the consumer test. Two cohorts were recruited from the greater Copenhagen area
163 and included seventy-five of the subjects, the Asian cohort (56 F, 19 M; mean age= 26.9 ±2.9; age
164 distribution: 56% aged 18–30 years and 44% aged 31–55 years; BMI= 21.6 ±3.6) and another
165 seventy-seven subjects, the Caucasian cohort (52 F, 15 M; mean age= 29.8 ±9.1; age distribution:
166 61% aged 18–30 years and 39% aged 31–55 years; BMI= 24.1 ±5.0). Seventy-two percentage of
167 Chinese subjects had been living in Denmark for less than two years at the moment of the test.
168 Informed, written consent was obtained from all subjects on the first test day. The present study was
169 performed according to the principles established by the Declaration of Helsinki and the protocol was
170 approved by the Institutional Ethics Committee of the University of Copenhagen.

171 *2.2 General procedure*

172 Participants attended one study session lasting 1 h and completed 4 different tasks: 1) a first
173 questionnaire to collect general demographic information followed by a second questionnaire to
174 identify subjects' mouth behavior; 2) Lingual tactile acuity task using three von Frey filaments; 3)
175 tongue pictures for the estimation of FPD; 4) a screening procedure for PROP responsiveness.

176 *2.3 Questionnaire to assess mouth behavior*

177 Participants' mouth behavior was assessed through a questionnaire, which was derived from the work
178 of Jeltema and collaborators (Jeltema, Beckley, & Vahalik 2014; 2015; 2016). There were 20 text-
179 based questions where subjects were asked to respond to a variety of statements aimed at
180 understanding how they preferred to manipulate food in their mouths. Additionally, 4 picture-based
181 questions were used to further evaluate the subjects' liking of a group of products from a mouth
182 processing perspective. These products were carefully chosen to represent those that would best
183 differentiate between groups. A Likert 6-point agree/disagree scale anchored 'strongly disagree' (1)

184 to ‘strongly agree’ (6) was used for all statements. The reader is referred to Table S1 (Supplementary
185 material) for the presentation of questions that were used to type individuals for MB.

186 *2.4 Lingual tactile acuity evaluation*

187 During the lingual tactile acuity evaluation blindfolded subjects were seated in an upright position
188 and their tongue stimulated or not with three von Frey filaments (no. 1.65, 2.36 and 2.44), one at a
189 time. The number of the filaments corresponds to a logarithmic function of the equivalent forces of
190 0.008, 0.02 and 0.04 g, respectively, according to the manufacturer (Aesthesio®: Precise Tactile
191 Sensory Evaluator, DanMic Global, LLC, San Jose, California, USA). For each filament, the subjects
192 were given 5 true and 5 mock touch exposures on the tongue’s apex. The stimulation order was
193 counterbalanced for the three filaments. The true touch with a filament was defined as ‘signal’ and
194 the corresponding response as either ‘hit’ or ‘not detected’. The responses from the mock exposures
195 were defined as ‘correct rejection’ or ‘false positive’. The subjects also rated their degree of certainty
196 in their response (either signal sure, signal not sure, no signal not sure, or no signal sure). From the
197 subjects' responses and certainty ratings *R-index values* (%) were calculated (O'Mahony, 1992). As
198 reported by Lee and Van Hout (2009), ‘the *R-Index* is an estimated probability of correctly identifying
199 a target stimulus (the signal) when presented pairwise with a 2nd stimulus (the noise). As frequently
200 happens with difference test, the R-Index values could range from 50% to 100%. If the subject cannot
201 discriminate between the 2 stimuli, the judge will have to guess and the chances of correctly
202 identifying the signal the *R-Index* will be 50%, otherwise the R-Index will be 100% if the judge can
203 discriminate perfectly between the 2 stimuli. Thus, the better the discrimination, the higher the value
204 will be’.
205

206 *2.5 Fungiform Papillae Density (FPD)*

207 The area to count individual FPD was selected following the procedure adapted from Bakke and
208 Vickers (2011) and previously described by Proserpio and colleagues (2016). Tongue pictures were
209 collected with blue staining, which was obtained by swabbing with blue food coloring, using a cotton-
210 tipped applicator. This fungiform papillae easily visible on the anterior portion of the dorsal surface
211 of the tongue. Digital pictures were recorded using a Canon digital camera (Canon EOS 700D) in a
212 brightly light room using the camera’s macro mode with no flash. The best photograph of each blue
213 stained tongue was selected to measure the FPD, and ImageJ software was used to mark the area in
214 which papillae were to be counted. A set of three 0.6 cm diameter circles was drawn on the front of
215 the anterior tongue, according to Bakke and Vickers, (2011). One operator, blind to any data

concerning subjects and with 3-year experience, counted FP in two different moment (at least 3 weeks between the first and second count). The counts were submitted to 1-way fixed ANOVA. Counts were considered valid if the operator effect was not significant ($p > 0.05$). FP were counted inside the three marked circles and the average count over the three circles was used for each subject (Proserpio et al., 2016). The Denver Papillae Protocol (Nuessle, Garneau, Sloan, & Santorico, 2015) was followed to determinate FP according to shape, color, size and recession. The individual FPD was then calculated by reporting the number of FP to a common unit area of 1 $cm^2$.

### *2.6 Taste responsiveness to PROP*

A method proposed by Prescott and colleagues (2004) was used for evaluating participants' PROP status. The intensity of bitterness of a supra-threshold 0.0032 M solution of PROP (European Pharmacopoeia Reference Standard, Sigma-Aldrich) was rated using the Generalized Labeled Magnitude Scale, gLMS (Bartoshuk et al., 2004), anchored at the top with the descriptor 'strongest imaginable sensation of any kind', which was defined in the context of all sensations, including painful ones. Practice on the use of the gLMS was provided to ensure that participants understood the scale and examples of the intensities of an array of ordinary sensory experiences (e.g., loudness of whispers, brightness of the sun) were provided. Then, subjects were presented with two identical samples (10 ml) and were instructed to hold each sample in their mouth for 10 s, then to expectorate the solution. After 20 s they were asked to evaluate the bitterness intensity. To control for carry-over effect, a 90s break was given to the subjects to rinse their mouths with water after the first sample evaluation (Laureati et al., 2018). The average of bitterness scores was used for each subject and respondents were grouped according to their PROP status based on arbitrary cut-offs. Non-tasters (NT) were 17.8% of total sample (arbitrary cut-off gLMS $\leq 17$, moderate), whereas Super-tasters (ST) were 36.2% (arbitrary cut-off gLMS $\geq 53$, very strong). The remainder of the respondents were considered as Medium-tasters (MTs) (Fischer et al., 2013; Hayes et al., 2010).

### *2.7 Data Analysis*

In order to identify the two major different Mouth Behavior styles among consumers, a latent class analysis with two classes was performed on the scores (6-point scale) for the 24 evaluated items of the questionnaire. The differences across clusters are identified by Wald test ($\chi^2$) along with p-values and $R^2$.

The association between population cohort, Mouth Behavior and tactile acuity (expressed as *R-index value*) was analysed by a Generalized Linear Model considering *Population cohort* (Danish and Chinese), *Mouth Behavior* groups ('Firm processing likers' and 'Soft processing likers') and

248 *Filament thickness* (no. 1.65, 2.36, 2.44) and their 2-way interactions as independent variables. Data
249 were further analyzed separately for Danish and Chinese considering *Mouth Behavior* groups ('Firm
250 processing likers' and 'Soft processing likers') and *Filament thickness* (no. 1.65, 2.36, 2.44) and the
251 respective interaction as independent variables in order to have better insights on the relative
252 contribution of these factors on dependent variables. Post-hoc comparisons using the Bonferroni test
253 adjusted for multiple comparison were conducted when appropriate.
254 The relationship between tactile acuity (*R-index* for the thinner filament no. 1.65), PROP
255 responsiveness and FPD was evaluated graphically and with Pearson's correlation r.
256 To determine the cross-cultural relationship between Mouth Behaviors and FPD, a Generalized
257 Linear Model was constructed with the FPD as dependent factor, and *Population cohort* (Danish and
258 Chinese), *Mouth Behavior* groups ('Firm processing likers' and 'Soft processing likers') and the
259 respective interaction as independent factors. To check for possible confounding or modulating
260 effects, the analysis was performed by adding *R-index values*, as covariate to the model. Additionally,
261 the same model was run using the mean intensity ratings of PROP responsiveness as dependent factor.
262 Both models have been run separately on Chinese and Danish subjects.
263 For all the analyses, a p-value of 0.05 was considered as threshold for statistical significance. Data
264 are presented as means with standard errors (SEM). Statistical analysis was performed using IBM
265 SPSS statistical software version 25 (SPSS Inc, Chicago, IL, USA). Latent class analysis was
266 performed in Latent Gold 5.1 (Statistical Innovations, Belmont, USA).
267

268 **3 Results**

269 *3.1 Mouth Behavior mapping*

270 Two distinct clusters were identified: Cluster 1 'Soft processing likers' with 79 participants and 'Firm
271 processing likers' composed of 73 participants. The number of participants in each cluster is listed in
272 **Table 1**.
273

274 **Table 1.** Numbers of participants in each MB group by population cohort.

| MB Group | Description | Chinese | Danish | Total |
|---|---|---|---|---|
| | | Number (%) | Number (%) | Number (%) |
| Firm processing likers (FPL) | Prefer foods that require to use the incisors and/or molars to break down rapidly or deform the food matrix | 17 (23%) | 56 (73%) | 73 (48%) |

| | | | | |
|---|---|---|---|---|
| Soft processing likers (SPL) | Prefer foods that could be held in the mouth for a longer time and manipulate them between the tongue and roof of the mouth | 58 (77%) | 21 (27%) | 79 (52%) |
| Total | | 75 | 77 | 152 |

For the two clusters significant differences were identified for 14 of the 24 questions used for the classification, results shown in **Figures 1**, with the questions sorted according to size of the difference. The most discriminating questions are Q8, Q18 and Q22 ($p<0.0001$) and regards soft smooth (banana/ripe peaches) versus more crunchy fruits (apples/pears), yogurt with crunchy versus softened muesli and finding or joy and pleasure consuming crunchy food as raw carrots, apples, peanuts coated with chocolate, crunchy granola or not. Questions that are best explained by the cluster are Q4 and Q18 ($R^2$ = 0.462 and 0.427) followed by Q22, Q8 and Q24 (**Table 2**). The 10 non-significant questions may be either not discriminating, were difficult to understand, or be more relevant for further subgrouping in larger population samples.

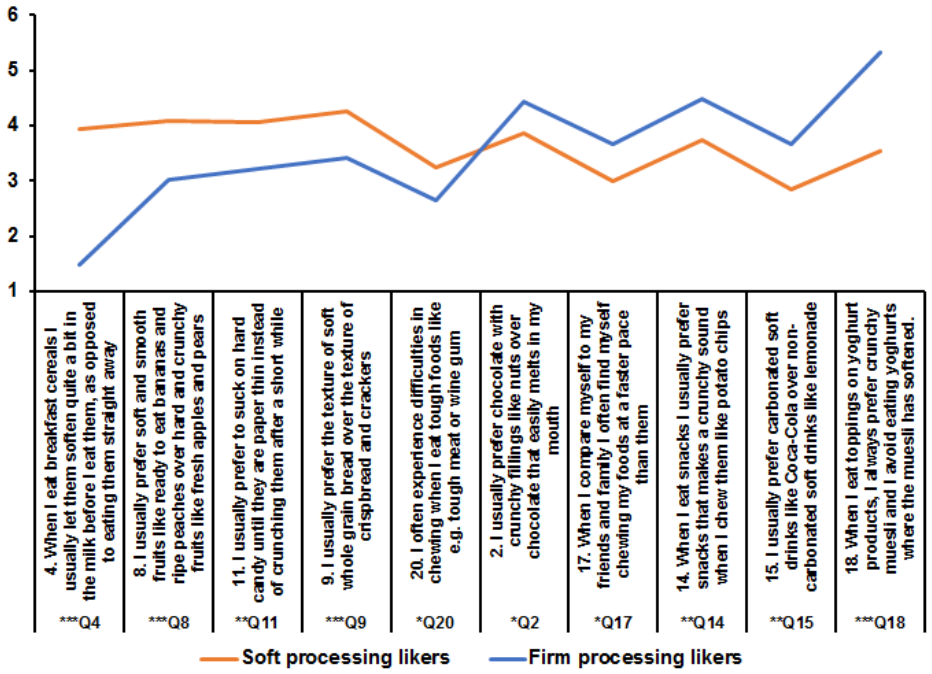
**Table 2.** Cluster means and statistical Wald, p-values and $R^2$ for the 24 indicators (questions).

| | | Means | | | | |
|---|---|---|---|---|---|---|
| | Items | Cluster 1 - Soft processing likers | Cluster 2 - Firm processing likers | Wald | p-value | $R^2$ |
| Q1 | I usually prefer a chewy piece of candy like e.g. wine gum over a hard piece of candy. | 3.79 | 3.88 | 0.13 | 0.72 | 0.001 |
| Q2 | I usually prefer chocolate with crunchy fillings like nuts over chocolate that easily melts in my mouth | 3.87 | 4.44 | 4.80 | 0.03 | 0.038 |
| Q3 | When I eat oranges I enjoy to put the slices into my mouth and suck the orange juice out of the slices instead of just chewing the slices right away | 2.96 | 2.47 | 2.88 | 0.09 | 0.024 |
| Q4 | When I eat breakfast cereals I usually let them soften quite a bit in the milk before I eat them, as opposed to eating them straight away | 3.95 | 1.48 | 13.11 | 0.001 | 0.462 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Q5 | When I eat chocolate I usually prefer chocolate with a good chewing texture over chocolate that easily melts in the mouth | 3.65 | 3.72 | 0.07 | 0.78 | 0.001 |
| Q6 | When I eat fruits I usually prefer crunchy fruits like fresh apples over more chewy fruits that I can chew on like pineapple or strawberries | 3.10 | 3.47 | 2.32 | 0.13 | 0.020 |
| Q7 | When it comes to chocolate I usually prefer chocolate that is hard enough to suck on over chocolate that quickly melts in my mouth | 3.35 | 3.44 | 0.17 | 0.68 | 0.001 |
| Q8 | I usually prefer soft and smooth fruits like ready to eat bananas and ripe peaches over hard and crunchy fruits like fresh apples and pears | 4.09 | 3.01 | 16.77 | < 0.0001 | 0.152 |
| Q9 | I usually prefer the texture of soft whole grain bread over the texture of crispbread and crackers | 4.27 | 3.43 | 11.37 | 0.001 | 0.102 |
| Q10 | When I eat ice cream I eat it right out of the freezer instead of letting it thaw a little | 3.43 | 3.71 | 0.90 | 0.34 | 0.007 |
| Q11 | I usually prefer to suck on hard candy until they are paper thin instead of crunching them after a short while | 4.07 | 3.21 | 7.79 | 0.005 | 0.076 |
| Q12 | I enjoy to eat foods that are smooth and easily spreads in my mouth like puddings and ice cream | 4.86 | 4.52 | 3.63 | 0.06 | 0.030 |
| Q13 | When I eat cake I usually prefer a chewy cake like brownie instead of a crunchy cake like biscuits | 4.40 | 4.33 | 0.10 | 0.75 | 0.001 |
| Q14 | When I eat snacks I usually prefer snacks that makes a crunchy sound when I chew them like potato chips | 3.73 | 4.49 | 10.27 | 0.002 | 0.089 |
| Q15 | I usually prefer carbonated soft drinks like Coca-Cola over non-carbonated soft drinks like lemonade | 2.84 | 3.66 | 7.21 | 0.007 | 0.061 |
| Q16 | When I eat sweets I usually prefer chocolate that easily melts in my mouth over hard candy that I would need to suck on | 4.20 | 3.88 | 1.83 | 0.18 | 0.015 |
| Q17 | When I compare myself to my friends and family I often find myself chewing my foods at a faster pace than them | 3.00 | 3.66 | 5.82 | 0.02 | 0.046 |
| Q18 | When I eat toppings on yoghurt products, I always prefer crunchy muesli and I avoid eating yoghurts where the muesli has softened | 3.53 | 5.33 | 18.11 | < 0.0001 | 0.427 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Q19 | I often find myself chewing foods on one side of the mouth only | 3.89 | 3.49 | 2.72 | 0.09 | 0.021 |
| Q20 | I often experience difficulties in chewing when I eat tough foods like e.g. tough meat or wine gum | 3.25 | 2.66 | 5.43 | 0.02 | 0.046 |
| Q21 | I find great joy and pleasure in consuming products like these that have a good chew (examples are chewy strawberry, jelly gums, whole grain bread, chewy biscuits, illustrated with photos) | 4.25 | 4.75 | 6.91 | 0.01 | 0.058 |
| Q22 | I find great joy and pleasure in consuming products like these that have a good crunch (examples are raw carrots, apples, peanuts coated with chocolate, crunchy granola, illustrated with photos) | 4.08 | 5.09 | 17.20 | < 0.0001 | 0.159 |
| Q23 | I find great joy and pleasure in consuming products like these that I can suck on until they dissolve (examples are oat meal, banana, chocolate pudding, ice cream, illustrated with photos) | 3.76 | 3.09 | 9.54 | 0.002 | 0.085 |
| Q24 | I find great joy and pleasure in consuming products like these that I can smoosh and I even smoosh foods that I could chew (examples are orange slices, hard candy, mints, chocolates without nuts and pieces, illustrated with photos) | 4.75 | 3.83 | 13.58 | 0.001 | 0.124 |

**a)**



**b)**

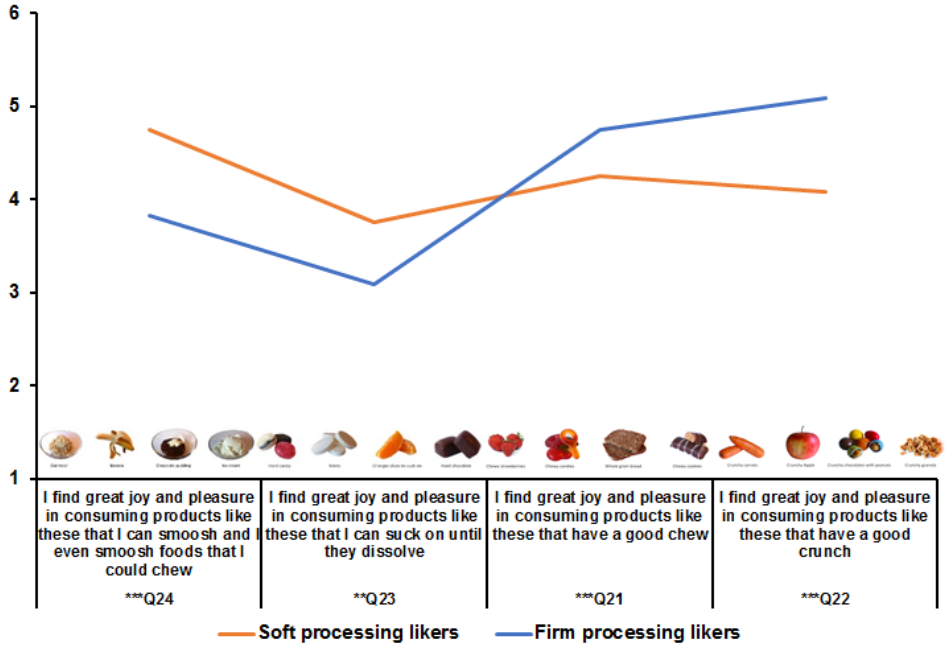



**Figure 1a-b.** Latent Class Analysis output regarding (a) significant text-based questions and (b) significant picture-based questions for Soft and Firm processing likers.

*3.2 Relationship between tactile acuity, population cohort and Mouth Behavior*

The Generalized linear model for tactile acuity showed that the main factors *Filament thickness* and *Mouth Behavior* were highly significant sources of variation (Wald $\chi^2$ =172.50, p <0.0001; *Mouth Behavior*: Wald $\chi^2$ =12.02, p <0.001, respectively). The main factor *Population cohort* presented a tendency toward significance (Wald $\chi^2$ =3.01, p =0.08). *Post-hoc* tests revealed significant higher *R-index values* when the tongue was stimulated with the thicker filament no. 2.44 (*R-index* = $91.7^a \pm 1.8$), as compared to stimulation with the filament no. 2.36 (*R-index*= $86.8^b \pm 1.8$), and the thinnest filament no. 1.65 (*R-index*= $71.6^c \pm 1.8$).

The *R-index values* were higher, although not significant, in Chinese (84.6 ± 1.1) compared to the Danish population cohort (82.0 ± 1.0). Similar results were found when analyzing the data according to signal detection theory (d-prime values).

Subjects characterized as 'Firm processing likers' obtained significant higher *R-index values* (85.9 ± 1.1) compared to subjects characterized as 'Soft processing likers' (80.7 ± 1.0).

The same model, conducted separately on Chinese and Danish subjects, indicated that the main factor *Filament Thickness* was a significant source of variation in both populations (Chinese: Wald $\chi^2$

313 =69.40, p <0.0001; Danish: Wald $\chi^2$ =71.38, p <0.0001). The main factor *Mouth Behavior* was a
314 significant source of variation for both Chinese (Wald $\chi^2$ =5.22, p <0.05) and Danish consumers
315 (Wald $\chi^2$ =7.17, p <0.01). Indeed, post-hoc tests revealed that 'Soft processing likers' obtained
316 significantly lower *R-index values* compared to 'Firm processing likers' in both population cohorts
317 (Chinese: SPL: 82.2 ± 1.9 *vs*. HPL: 87.1 ± 1.0 and Danish: SPL: 79.3 ± 1.7 *vs*. HPL: 84.7 ± 1.1).
318 None of the 2-way interactions were significant.

319 *3.3 Relationship between tactile acuity, PROP status and Fungiform Papillae Density*
320 The characteristics of participants in each population cohort are listed in **Table 2**.

321 **Table 2.** Subjects' characteristics according to PROP status and FPD in Chinese and Danish
322 population cohorts.

| PROP status | Chinese | | Danish | | Total | |
|---|---|---|---|---|---|---|
| | n | FP/cm$^2$ (mean ±SEM) | n | FP/cm$^2$ (mean ±SEM) | n | FP/cm$^2$ (mean ±SEM) |
| Supertaster (ST) | 36 | 69.7 ±2.9 | 19 | 62.5 ±3.8 | 55 | 67.2 ±2.4 |
| Medium taster (MT) | 29 | 57.4 ±3.9 | 41 | 57.7 ±2.6 | 70 | 57.6 ±2.1 |
| Non taster (NT) | 10 | 66.1 ±5.4 | 17 | 46.1 ±4.1 | 27 | 53.5 ±3.4 |

323

324 No correlations were found between the tactile acuity (*R-index*) and the other two variables
325 considered. Additionally, the subject's ratings of the bitterness of the PROP solutions was positively
326 correlated with the FPD (r =0.28; p <0.001; $R^2$ =0.08), although with a very low Pearson's correlation.
327 Notably, no significant correlation in the Chinese population cohort was found (r = 0.17, p = 0.15; $R^2$
328 =0.03).

329 *3.4 Cross-cultural differences in Mouth Behaviors in relation to FPD and to PROP status*

330 A summary of the main results obtained through the Generalized Linear Model to determine the
331 cross-cultural relationship between Mouth Behaviors and FPD and PROP has been reported in **Table**
332 **3**.

333 **Table 3.** Summary of the main results obtained through the Generalized Linear Model to determine
334 the cross-cultural relationship between Mouth Behaviors and FPD and PROP.

| Phenotypical marker | Chinese | Danish |
|---|---|---|

| | FP/cm$^2$ (mean ±SEM) | FP/cm$^2$ (mean ±SEM) | p-value |
|---|---|---|---|
| FPD | 62.9 ±1.4 | 56.6 ±1.3 | < 0.001 |
| PROP responsiveness | 51.4 ±2.0 | 38.3 ±1.9 | < 0.0001 |

A significant effect of *Population cohort* on subjects' FPD (Wald $\chi^2$= 10.67; p <0.001) and PROP responsiveness (Wald $\chi^2$ = 21.78; p <0.0001) was found, with Chinese population cohort characterized by a greater FPD and a greater responsiveness to PROP compared to Danish consumers. The main factor *Mouth Behavior* and the interaction factor *Population cohort* x *Mouth Behavior* were not a significant source of variation on FPD and PROP responsiveness.

Interestingly, when the relationship between Mouth Behaviors and FPD was analyzed separately on Chinese and Danish subjects, the main factor *Mouth Behavior* have been found as significant source of variation only in Chinese population cohort (Wald $\chi^2$ =4.25, p <0.05), with Chinese 'Soft processing likers' characterized by a greater FPD (65.8 ±1.4 FP/cm$^2$) than 'Firm processing likers' (59.9 ±2.5 FP/cm$^2$). No significant effect has been highlighted running the same model considering the main factor *Mouth Behavior* in relation to PROP responsiveness.

## 4 Discussion

With focus on the two major groups of MB, quantitative latent class analyses (McCutcheon, 1987; Magidson & Vermunt, 2004; Vermunt & Magidson, 2005) was used for the classification of preferred mouth behavior. This approach deviated from that proposed by Jeltema and colleagues (2014), in which subjects were forced to choose the type of mouth behavior most desirable to them based on a pictorial presentation of different foods and, at the same time, to indicate what mouth behavior they rejected most. This approach was reported to be more accurate in separating behavioral groups than the standard surveys (Jeltema, Beckley, & Vahalik, 2015). However, it is important to note that just because a person claims to prefer a specific mouth behavior, does not mean that the others are rejected. Indeed, even though a person may generally like soft textures, and often chose foods that could be smooshed or sucked, it could be possible that (s)he may also prefer hard texture foods for other reasons, making the classification in the subgroups of Jeltema and colleagues difficult. Moreover, texture preferences could also be potentially affected by characteristics related to food product itself, such as flavor, particle size, matrix type, fat content and microstructure, and/or related to consumers psychological and physiological factors, such as consumer's familiarity, expectations and sensitivity.

To segment our subjects in relation to their preferred mouth behavior, the present study used a quantitative alternative, the latent class analysis which has several advantages: it is a statistical method and probability based, all relevant information about the respondents perception of mouth behavior can be taken into account (in this case the scoring of the 24 items on a 6 point ordinal scale), the output includes for each respondent the probability to belong to each of the clusters and the classification is based on the highest probability. Furthermore, the relationship between the items and the clusters is also based on probabilities and the level of significance for each of the 24 items is included.

In the present study, with two clusters the broad categorization of preferred oral food processing into 'Firm processing likers' and 'Soft processing likers' was confirmed. Besides, the two classes of preferred MB showed, that the Danish Caucasian population with 73% 'Firm processing likers' had similarity to the North American population reported by Jeltema and colleagues (2014). In their study among 500 participants 76% had preferences for foods that needed firm processing on biting and chewing (33% Crunchers and 43% Chewers). The two populations of Chinese and Danish subjects showed distinct differences in preferred food oral processing behaviors. The Chinese population was characterized by a larger number of 'Soft processing likers' (77% of the population), who preferred foods that could be held in the mouth for a longer time and manipulated between the tongue and roof of the mouth. On the contrary, Danish consumers mostly belonged to the 'Firm processing likers' group, who preferred foods that require using the incisors and/or molars to break down or deform the food in the mouth. A further classification of participants in subgroups of respectively 'smooshers' and 'suckers' and 'chewers' and 'crunchers', as suggested by Jeltema and colleagues (2014), was not feasible due to the limited sample size.

Chinese population in the present study deviated significantly from the Caucasian with much higher preferences for soft food processing in the mouth. These results may indicate that cultural and dietary habits in food consumption (e.g. cooked, refined (noodles) foods *vs* less cooked, less refined (rye bread) foods) may influence the preferred oral texture processing between Asians and Caucasians. The large differences also suggest that Chinese participants, living in Denmark for less than two years, did not adapt towards similar texture preferences as the Danish consumers (who had been resident since birth). Other studies have indeed shown that Chinese beliefs and food preferences persist up to twenty years after moving to a foreign country and continue even in subsequent generations (Murray, Easton, & Best, 2001).

It should be noted that preferred MB does not necessarily relate to preferred oral texture perception. Differences in tactile acuity as measured with the von Frey filaments showed that Chinese subjects are equally sensitive across the range of fibers as Danish subjects, confirming previous results

397 reported by Essick and colleagues (2003). Moreover, the group of 'Firm processing likers' were
398 shown to be more sensitive than the 'Soft processing likers' in both population cohorts. Thus results,
399 suggested that lingual acuity did not play a role in subjects' decreased preferences of foods rich in
400 texture. Perhaps other aspects than tactile acuity, such as culturally-driven experience and familiarity
401 with foods as discussed above, have a more influencing role in establishing food texture preferences.
402 Previous studies found that lingual tactile thresholds were significantly associated with FPD, such
403 that higher densities resulted in greater tactile acuity (Bangcuyo & Simons, 2017; Essick, Chopra,
404 Guest, & McGlone, 2003). Moreover, several studies have found correlations between PROP
405 intensity and texture perception (Bakke & Vickers, 2011; de Wijk et al., 2007; Hayes & Duffy, 2007;
406 Pickering, Simunkova, & Di Battista, 2004; Pickering & Robert, 2006). A reasonable explanation has
407 been that PROP intensity is related to FPD, which in turn is related to trigeminal innervation.
408 However, to our knowledge, no direct association has been shown to exist between the density of
409 trigeminal (tactile) innervation and the density of taste buds and/or fungiform papillae. Indeed, the
410 areas between fungiform papillae are also innervated and could conceivably be more densely
411 innervated in subjects with a lower density of papillae. Nevertheless, our study failed to establish a
412 direct correlation between tactile acuity and PROP responsiveness or FPD, as previously suggested
413 (Bangcuyo & Simons, 2017; Essick, Chopra, Guest, & McGlone; 2003). This could be due to the
414 different tasks used to measure tactile acuity in this study (von Frey Filaments) compared to the
415 previous ones (letter-recognition tasks). Moreover, in the present study we only measured mechanical
416 stimulation and not orientation, which perhaps more likely could highlight differences related to
417 morphological variables. As previously reported, the relationship between FPD and PROP has been
418 extensively studied, since both measures have been used as indices of taste sensitivity in general.
419 Many studies have reported a positive relationship between these two measures, but the magnitude
420 of this association has shown considerable variation, ranging from relatively high Pearson's r values
421 $> 0.8$, to moderate ($r \leq 0.5$) and low ($r \leq 0.3$) (see Piochi, Dinnella, Prescott, & Monteleone, 2018 for
422 a review). Consistent with some of these studies, we found that FPD and perceived PROP intensity
423 were correlated with each other, but presented a low Pearson's r value. No association was found in
424 the Chinese population cohort, with some overlap among the three PROP status groups. Moreover,
425 looking at the subjects' characteristics according to PROP status and FPD in Chinese and Danish
426 population cohorts, it is possible to observe that Chinese presented a great variability in FPD, with
427 NT subjects characterized by a similar density as the STs. A possible explanation for these unexpected
428 findings is that populations with different genetic admixtures were studied, and the presence of more
429 extreme phenotypes in some populations relative to others (e.g. a greater number of ST in Asians
430 compared to the Caucasians) may be driving the observed effects (Barbarossa et al., 2015; Tepper,

431 2008). Moreover, several recent studies have failed to find a significant relationship between FPD
432 and PROP phenotype (Dinnella et al., 2018; Fisher et al. 2013; Garneau et al. 2014), and other factors
433 than polymorphism of TAS2R38 have been hypothesized as possible variables involved in FPD
434 variation (e.g. polymorphisms of gene controlling for gustin functionality) (Barbarossa et al., 2015;
435 Calò et al., 2011; Melis et al., 2013; Padiglia et al., 2010).
436 As far as we know, this is the first study to investigate the relationship between morphological and
437 phenotypical data (FPD and PROP responsiveness) and preferred oral processing behavior. Chinese
438 consumers generally presented a greater responsiveness to PROP and were characterized by a greater
439 FPD compared to Danish consumers. However, our results suggest that the cross-cultural differences
440 found in preferred Mouth Behaviors seem not to be associated with FPD and PROP responsiveness.
441 Thus, we conclude that oral processing behaviors appear to involve other perceptual mechanisms that
442 are unrelated to morphological or phenotypical subject characteristics. For this reason, due to the
443 complex nature of texture perception and preferences, it is essential to identify other relevant factors
444 and define characteristics that govern the processes involved.
445 While research findings from this work are significant, limitations of the study should also be noted.
446 The first limitation of our study is the relatively small sample size, not balance for gender. While
447 there were several statistically significant observations, the findings may not be generalized to the
448 entire Chinese and Danish populations, and it is recommended to extend the number of subjects
449 involved in the experiment in order to avoid 'false positive' associations and obtain a more robust
450 and generalizable outcome. Another issue to be noted is that the evaluation of taste sensitivity is
451 limited to PROP responsiveness and FPD evaluation and these two general markers for taste
452 sensitivity still present contradictory relationship between each other and between perception of basic
453 tastes (see Piochi, Dinnella, Prescott, & Monteleone, 2018 for a review). Thus, a combination of taste
454 perception measurements, such as data related to fundamental taste thresholds, should be included to
455 better characterize the overall subjects' perception. Moreover, the use of the von-Frey filaments for
456 detection threshold could be insufficient for this task due to the fact that the lowest available force
457 (0.008 g) could not be sensible enough to establish the real detection threshold of the subjects. Thus,
458 different tongue sensitivity methods (e.g. Luneau Cochet-Bonnet aesthesiometers) (Miles et al., 2018)
459 could be employed to measure touch detection threshold since these aesthesiometers had the benefit
460 of providing an increased number of extremely lower-force stimuli than the filaments. Additionally,
461 two-point discrimination task and stereognostic letter-recognition task could be used to evaluate the
462 roughness sensitivity and the point-and-edge sensitivity, respectively, in order to include
463 discrimination of size and orientation. However, it should be noted that the latter method could not

be suitable for cross-cultural studies among populations with very different handwritten characters (e.g. Latin *vs* Chinese alphabet characters).

It would be necessary in future researches to investigate whether lingual tactile acuity is related to sensitivity toward, rather than preference for, textural aspects of foods. For example, particle detection could be associated to lingual tactile acuity and, therefore, could highlight more evidence about how subjects perceive and prefer foods.

## Conclusion

Cross-cultural differences in preferred oral processing behavior were found, as Chinese subjects predominantly preferred to manipulate foods between the tongue and roof of the mouth. On the contrary, Danish subjects mostly preferred to use the teeth to break down foods in the mouth. Chinese subjects presented differences in oral tongue anatomy as shown by greater FPD and PROP responsiveness compared to Caucasian Danish subjects.

A significant but low correlation was found between PROP status and FPD, while no direct correlation between tactile acuity and PROP responsiveness or FPD were found. The reason of having no direct correlation between subjects' ability in touch detection and morphological and phenotypical data (FPD and PROP status) is still not certain. These observations suggest that thoughtfulness should be applied in studying texture perception, since focusing solely on PROP and FPD evaluation may be not sufficient to understand the variability and complexities of phenomena raised from the interaction between food and mechanoreceptors in the oral cavity. Thus, the physiological parameters that we investigated should be examined in more detail (e.g. PF size and relevant distributions, more sensitive method to valuate touch detection). Moreover, this study provides evidence that cultural background could represent a strong influence in the oral process preference for texture.

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## Competing interests

The authors have declared that no competing interests exist.

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686 **Supplementary material**

687

688 **Table S1.** Types of questions used in the survey to place individuals into Mouth Behavior groups.

| | Questions |
|---|---|
| 1 | I usually prefer a chewy piece of candy like e.g. wine gum over a hard piece of candy |
| 2 | I usually prefer chocolate with crunchy fillings like nuts over chocolate that easily melts in my mouth |
| 3 | When I eat oranges I enjoy to put the slices into my mouth and suck the orange juice out of the slices instead of just chewing the slices right away |
| 4 | When I eat breakfast cereals I usually let them soften quite a bit in the milk before I eat them, as opposed to eating them straight away |
| 5 | When I eat chocolate I usually prefer chocolate with a good chewing texture over chocolate that easily melts in the mouth |
| 6 | When I eat fruits I usually prefer crunchy fruits like fresh apples over more chewy fruits that I can chew on like pineapple or strawberries |
| 7 | When it comes to chocolate I usually prefer chocolate that is hard enough to suck on over chocolate that quickly melts in my mouth |
| 8 | I usually prefer soft and smooth fruits like ready to eat bananas and ripe peaches over hard and crunchy fruits like fresh apples and pears |
| 9 | I usually prefer the texture of soft whole grain bread over the texture of crispbread and crackers |
| 10 | When I eat ice cream I eat it right out of the freezer instead of letting it thaw a little |
| 11 | I usually prefer to suck on hard candy until they are paper thin instead of crunching them after a short while |
| 12 | I enjoy to eat foods that are smooth and easily spreads in my mouth like puddings and ice cream |
| 13 | When I eat cake I usually prefer a chewy cake like brownie instead of a crunchy cake like biscuits |
| 14 | When I eat snacks I usually prefer snacks that makes a crunchy sound when I chew them like potato chips |
| 15 | I usually prefer carbonated soft drinks like Coca-Cola over non-carbonated soft drinks like lemonade |
| 16 | When I eat sweets I usually prefer chocolate that easily melts in my mouth over hard candy that I would need to suck on |
| 17 | When I compare myself to my friends and family I often find myself chewing my foods at a faster pace than them |
| 18 | When I eat toppings on yoghurt products, I always prefer crunchy muesli and I avoid eating yoghurts where the muesli has softened |

| | |
|---|---|
| 19 | I often find myself chewing foods on one side of the mouth only |
| 20 | I often experience difficulties in chewing when I eat tough foods like e.g. tough meat or wine gum |
| 21 | Please look at the picture and state to what extent you agree with the following statement:<br>I find great joy and pleasure in consuming products like these that have a good chew<br>(Please consider all four products as a group, and consider your liking as an average for all four products) |

Chewy strawberries

Chewy candies

Whole grain bread

Chewy cookies

| | |
|---|---|
| 22 | Please look at the picture and state to what extent you agree with the following statement:<br>I find great joy and pleasure in consuming products like these that have a good crunch<br>(Please consider all four products as a group, and consider your liking as an average for all four products) |

Crunchy carrots

Crunchy Apple

Crunchy chocolates with peanuts

Crunchy granola

| | |
|---|---|
| 23 | Please look at the picture and state to what extent you agree with the following statement:<br>I find great joy and pleasure in consuming products like these that I can suck on until they dissolve<br>(Please consider all four products as a group, and consider your liking as an average for all four products) |

Hard candy

Mints

Oranges slices to suck on

Hard chocolate

| | |
|---|---|
| 24 | Please look at the picture and state to what extent you agree with the following statement:<br>I find great joy and pleasure in consuming products like these that I can smoosh and I even smoosh foods that I could chew<br>(Please consider all four products as a group, and consider your liking as an average for all four products) |

Oat meal | Banana | Chocolate pudding | Ice cream