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A review on oral tactile sensitivity: measurement techniques, influencing factors and its relation to food perception and preference

Jing Liu[a,*,1], Camilla Cattaneo[b,1], Maria Papavasileiou[a], Lisa Methven[c], Wender L.P. Bredie[a,*]

[a] Department of Food Science, Section for Food Design and Consumer, University of Copenhagen, Rolighedsvej 26, 1958 Frederiksberg C, Denmark
[b] Sensory & Consumer Science Lab (SCS_Lab), Department of Food, Environmental and Nutritional Sciences, University of Milan, Milan 20133, Italy
[c] Department of Food and Nutritional Sciences, University of Reading, Whiteknights, Reading RG66AP, UK

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ABSTRACT

Texture perception and mouthfeel are important factors in food acceptance and rejection. Despite the contribution of oral tactile sensation to perception of food texture, it has been understudied. This review addresses oral tactile sensitivity in relation to measurement methods, factors that influence sensitivity, and its association with texture perception and preference. Notably, the advantages and disadvantages of different testing methods are discussed, including the two-point discrimination task (or two-pin test), the grating orientation test, the letter-identification test, point pressure sensitivity by filaments, and discrimination tests for specific aspects of texture. The effects of age, sex, fungiform papillae, ethnicity, pathological changes and other physiological measures on oral tactile sensitivity are also reviewed. The oral tactile sensitivity tends to decline with advanced age in healthy adults; some pathological changes may have negative influence on the tactile sensitivity; however, the effect of several other factors are contradictory in the literature. Regarding the association between oral tactile sensitivity and texture perception and food preferences, it is suggested that the sensitivity measured by techniques such as the two-point discrimination task or a grating orientation task typically represents a single dimension of texture perception and thus is difficult to link directly to perception of other texture dimensions. The sensitivity to specific texture attributes such as thickness might predict texture perception and preference. The review stresses the importance of further research in oral tactile sensitivity and its role in the perception and liking of various food textures.

1. Introduction

Texture and mouthfeel are fundamental sensory properties of foods and beverages. However, despite the important contribution of oral texture perception to eating behavior (Forde, Van Kuijk, Thaler, De Graaf, & Martin, 2013; Santagiuliana, Bhaskaran, Scholten, Piqueras-Fiszman, & Stieger, 2019), the modality of texture has been referred to for many years as ‘the forgotten one’ because it has demanded little attention in comparison to taste and flavour (Guinard & Mazzucchelli, 1996; Proserpio, Bresciani, Marti, & Pagliarini, 2020). Texture cannot be presented by any single attribute or characteristic but by a combination of multiple ones (Szczesniak, 2002). Indeed, Szczesniak in 1963 defined texture as “the sensory manifestation of the structure of the food and the manner in which this structure reacts to the applied forces, the specific senses involved being vision, kinesthesis, and hearing” (Szczesniak, 1963). This multi-dimensional and dynamic nature of food texture makes it difficult to evaluate oral texture sensitivity by human subjects and to establish a relationship to food texture preferences. Oral tactile sensitivity can be studied by psychophysical methods with defined stimuli for touch, spatial distance and discrimination between object sizes and shapes such as in oral stereognosis (Jacobs, Serhal, & Steenberghe, 1998). Besides these psychophysical tests, biological markers such as the fungiform papillae density on the tongue (Bangcuyo & Simons, 2017; Essick, Chopra, Guest, & McGlone, 2003) may be related to possible differences in oral tactile acuity. However, it is still ambiguous how useful these basic measures are in relation to prediction of texture perception of foods as well as can predict texture preferences.

The aim of this review is to first present different methods testing oral tactile sensitivity and discuss the advantages and disadvantages of each measurement technique. The effects of age, sex, fungiform papillae,

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[*] Corresponding authors.
E-mail addresses: ljing@food.ku.dk (J. Liu), wb@food.ku.dk (W.L.P. Bredie).
[1] These authors contributed equally to this work.

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Table 1
Summary of different methodology in measuring oral tactile sensitivity.

Test method	Determination	Methodological challenges
Two-point discrimination	Subject's tactile spatial resolution	- Subject might use non-spatial cues (i.e. movement of the probe or oral surface) to distinguish one from two points - The tool might not be sufficiently sensitive - Poor test retest reproducibility
Grating orientation test	Subject's tactile spatial resolution	- Cognitive involvement - Subject might use non-spatial cues (i.e. movement of the probe or oral surface) to distinguish vertical or horizontal grating - Require specialized pre-constructed stimulus objects, which span a fixed spatial range
Letter-identification test	Subject's tactile acuity	- Spatial properties and ability to cognitively integrate and identify the letter - Not necessarily just spatial recognition - Less suitable for cross-cultural studies if differences in alphabets exist
Point pressure by monofilaments or aesthesiometers	Subject's touch pressure sensitivity	- Presence or absence rather than resolution of patterns - The tool might not be sufficiently sensitive due to too high fibre diameter - Inter-device variability
Point air pressure test	Subject's touch pressure sensitivity and acuity	- Can be used for areas in the oral cavity that are difficult to reach with monofilaments

ethnicity, pathological changes and other factors on oral tactile sensitivity are also reviewed. In addition, the association between oral tactile/texture sensitivity and food texture perception and preference is discussed. It is worth noting that in this review oral tactile sensitivity is measured with specific methods with defined stimuli, whereas oral texture sensitivity is defined the sensitivity to specific texture attributes in the food.

2. Methodology in measuring oral tactile sensitivity

The somatosensory system encompasses nerves under the skin's surface that conduct information to the central and peripheral nervous systems leading to the sensations of touch, pain, pressure, temperature and proprioception (Carlson, 2012; Haggard & de Boer, 2014; Kohyama, 2015). Presso-receptors, mechanoreceptors and thermo-receptors in oral cavity sensory cells are responsible for the oral touch sensations, while receptors localized in the mucosa, jaw and teeth act in the perception of the granulometry and consistency of foods, respectively. Information about the shape, size and texture of foods during oral exploration by the tongue are provided by the proprioceptive system (Carlson, 2012; Haggard & de Boer, 2014; Kohyama, 2015).

Much of scientific knowledge related to the perception of texture in the mouth is derived from findings in the hands where four major classes of mechanoreceptors have been identified (Abraira & Ginty, 2013; Foegeding, Vinyard, Essick, Guest, & Campbell, 2015; Roudaut et al., 2012). Two classes are slowly adapting (SA) receptors - identified as SAI (associated with Merkel's disks) and SAII (associated with Ruffini endings) - and respond to sustained static stimulation, particularly to edges and points or skin stretch. The other two classes are rapidly adapting (RA) receptors - identified as RAI (associated with Meissner corpuscles) and RAII (associated with Pacinian corpuscles) - which respond primarily to changes in stimulation, such as general skin motion and vibration. The surface of the oral cavity is innervated by the same nerve fibres as the non-hairy skin of the hands and fingers, with the possible exception of RAII mechanoreceptors which are yet to be found in oral surfaces (Bukowska, Essick, & Trulsson, 2009; Johansson, Trulsson, Olsson, & Westberg, 1988; Trulsson & Essick, 1997; Trulsson & Johansson, 2002). One type of mechanoreceptor type does not directly code for a specific texture modality, rather each modality is likely to be coded by a combination of signals (Foegeding et al., 2015; Linne & Simons, 2017). Thus, the specific textural modalities perceived during the consumption of foods, such as viscosity, roughness or smoothness, result from the integration of signals registered by SA and RA during higher processing in the brain.

In summary, texture is determined by various parameters which are combined together, underscoring the difficulties in researching this particular aspect of food (Szczesniak, 2002). Therefore, a single method to measure texture sensitivity is unlikely to prove sufficient. It is likely that a suite of effective and repeatable test to evaluate a variety of texture modalities is needed. Table 1 summarizes different methodology in measuring oral tactile sensentivity.

2.1. *Two-point discrimination task*

Various methods have been used to determine oral tactile acuity to gain further insight into its contribution to food texture perception. A two-point discrimination task has been one of the primary measurement techniques (Ringel & Ewanowski, 1965). This method has been a standard since the 1860s and commonly used for determining the tactile spatial resolution in a subject. The task requires that 2 punctiform stimuli (e.g., two pins) that can be recognized as two distinct points, are lightly pressed onto the anterior part of the subject's tongue. The separation of the pins ranged from 0 to 8 mm, using the staircase method, with steps of 1 mm (Engelen & Van Der Bilt, 2008). This method determines a spatial threshold at which the two distinct punctiform stimuli can be distinguished from one. At each presentation, the subject is asked to indicate whether 1 or 2 stimulus points are perceived (Engelen, Van der Bilt, & Bosman, 2004). However, it has been questioned whether the two-point discrimination task really characterises tactile spatial resolution. Van Boven and Johnson (1994a) suggested that the subject might use non-spatial cues (i.e. movement of the probe or oral surface) to distinguish one from two points, and in such circumstances the subject's performance could exceed their true spatial resolution limit.

2.2. *Grating orientation task*

Another task to measure a subject's tactile spatial acuity is the grating orientation task. This task was developed and validated by Van Boven and colleagues (1994b) to provide clinicians and researchers with an alternative means to assess spatial acuity that overcame the limitations of the two-point discrimination task. The task consists of blocks engraved with ridges (gratings) on their surface. Gratings have equal groove and bar widths, e.g., 0.2, 0.25, 0.5, 0.75, 1.00 and 1.25 mm (Appiani, Rabitti, Methven, Cattaneo, & Laureati, 2020) or 0.35, 0.5, 0.75, 1.00, 1.25, 1.5, 2.00 and 3.00 mm for the JVP domes (Stoelting Co, Wood Dale, IL, USA). The block has an overall size of 1 cm^2, which allows to cover an area of the tongue with multiple receptor sites; this is quite different to the two-point discrimination test. The blocks are positioned on blindfolded subject's tongue, who is asked to recognize the orientation (horizontal *vs.* vertical) of the ridges. To avoid cognitive difficulties in articulating the possible orientation of the grooves, the subjects could use his/her hand to indicate the orientation.

The task has been used to assess lingual spatial resolution both in a group of adults (Van Boven & Johnson, 1994b) and recently in children (Appiani et al., 2020). However, also in this case some authors raised concerns about the feasibility of test, since cognitive confounds may affect the answers given by subjects when they are asked to recognize grating orientation, as well as non-spatial cues (e.g., lateral movement of the tongue) on which subjects based their responses could be generated.

2.3. Letter-identification task

In order to overcome some of the limitations in two-point and grating tasks, Essick and colleagues developed in 1999 a letter-identification task, asking subjects to use their tongues to identify letters of the alphabet of varying sizes embossed onto Teflon strips (Essick, Chen, & Kelly, 1999). The identification of a 3-D sub-set of the Latin alphabet letters (printed or embossed) may also assess aspects of oral stereognosis, the ability to distinguish size, shape, and orientation of stimuli (Boliek, Rieger, Li, Mohamed, Kickham, & Amundsen, 2007; Jacobs, Bou Serhal, & van Steenberghe, 1998). The letter recognition task is thought to provide stimuli that are still identifiable on the basis of shape, while limiting at the same time the use of non-spatial cues in discrimination. Although stereognosis tasks do assess tactile acuity, there is also a cognitive component associated with letter/shape identification (Miles, Ang, & Simons, 2020). Variability identified in subjects' tactile acuity or the quality of answers given by the subjects, may not necessarily be attributable to tactile differences alone. Indeed, this task is inappropriate to use in countries that do not use the Latin alphabet (Cattaneo, Liu, Bech, Pagliarini, & Bredie, 2020). However, these tasks have been used in a number of studies designed to evaluate tactile acuity and how it relates to a variety of factors (Bangcuyo & Simons, 2017; Essick et al., 2003; Lukasewycz & Mennella, 2012; Steele, Hill, Stokely, & Peladeau-Pigeon, 2014). For example, it has been used to study possible connections between lingual tactile acuity and responsiveness to the bitter compounds 6-n-propylthiouracil (PROP) as well as fungiform taste bud density in Asian women, demonstrating a positive relationship between PROP bitter sensitivity and tactile acuity (Essick et al., 2003). Letter-identification has also been used to investigate possible connections between oral tactile acuity and age (Bangcuyo & Simons, 2017; Steele et al., 2014), and more specifically between food texture preferences of children and their mothers (Lukasewycz & Mennella, 2012) as discussed further in section 3.1.

2.4. Pressure sensitivity by filaments and aesthesiometers

Recently, various laboratories have used monofilaments that measure pressure sensitivity to gain further insight into lingual tactile acuity. This tool has been commonly used in the medical field to assess the tactile sensitivity of hands and feet, to diagnose diseases such as hypesthesia (i.e., abnormally decreased sensitivity to touch stimuli) and dysesthesia (i.e., abnormally increased sensitivity to touch stimuli). Different types of monofilaments are commercially available from various sources. A number of studies have used von Frey/Semmes-Weinstein monofilaments to measure punctate pressure detection on the tongue (Appiani et al., 2020; Breen, Etter, Ziegler, & Hayes, 2019; Cattaneo et al., 2020; Etter, Miller, & Ballard, 2017; Liu, Bech, Stolzenbach, & Bredie, 2021; Pigg, Baad-Hansen, Svensson, Drangsholt, & List, 2010; Santagiuliana et al., 2019; Yackinous & Guinard, 2001; Zhou et al., 2020). Both von Frey and Semmes Weinstein instruments provided in a range of different thickness filaments that exert a set force upon bending. In both cases the smallest filament exerts a force of 0.008 g (0.08 mN). However, several of the aforementioned studies highlighted that these filaments might not be a sufficiently sensitive tool to evaluate oral tactile sensitivity, as the lowest available force (0.08 mN) is higher than the reported sensitivity level of the tongue mucosa (Trulsson & Essick, 1997). Thus, more recent studies used the Luneau Cochet-Bonnet aesthesiometers to obtain a more sensitive measurement that was not possible in past studies. Compared to monofilaments, aesthesiometers have various benefits: i) they can provide an increased number of extremely low-force stimuli (the lightest measured force is 0.0044 g); ii) they can reduce the inter-device variability due to the force adjustability being from a single device; and iii) they can reflect sensitivity to mechanical pressure (force per unit area) unambiguously since the filament's surface area remains constant as mechanical force is varied (Miles, Van Simaeys, Whitecotton, & Simons, 2018). However, there are also limitations in using Luneau Cochet-Bonnet aesthesiometers for example unresolved questions related to calibration of Cochet-Bonnet devices and ability to share findings across studies (Etter, Breen, Alcala, Ziegler, & Hayes, 2020).

2.5. Discrimination tests for specific aspects of texture

In addition to punctate pressure sensitivity, the evaluation of fine surface roughness offers another type of tactile stimulus that is free from cognitive confounds. However, unlike the monofilaments or aesthesiometers, there is not an established and validated instrument for the evaluation of this attribute. Previous studies on the fingertip have utilized commercially available products, such as abrasive papers and fabrics (Bensmaïa & Hollins, 2005; Miyaoka, Mano, & Ohka, 1999), while others have recently used polymer custom-made stimuli, directionally roughened (Skedung, Arvidsson, Chung, Stafford, Berglund, & Rutland, 2013) to evaluate fine surface roughness. Only a single study focuses on the oral cavity using directionally roughed metal bars, having small but discrete changes in roughness (Linne & Simons, 2017). Few studies have been conducted using model/real food to measure such specific aspects of texture (Breen et al., 2019; Puleo, Miele, Cavella, Masi, & Di Monaco, 2019). In particular, Breen and colleagues (2019) studied the perception of grittiness, using chocolate as a model food. They measured subjects' discrimination thresholds for oral point pressure using von Frey filaments and the discrimination of particle size in chocolates by means of just-noticeable-difference (JND) thresholds. Subjects were classified according to their discrimination thresholds for oral point pressure using Von Frey filaments, and tested for their ability to discrimination between two commercial chocolates of difference particle sizes. The group with better oral acuity were more able to discriminate between the chocolates. Similarly, Puleo et al. (2019) developed a methodology to investigate individual discrimination sensitivity to different levels of graininess in cocoa-based creams, obtained by changing refining time.

Thickness is the sensory attribute most commonly used to describe the viscosity of beverages. The capability to discriminate differences in the viscous nature of food and subsequent perception is another factor that may be linked to individual's tactile sensitivity. The capability of viscosity discrimination among individuals has been evaluated with many Newtonian and non-Newtonian liquids studying Just Noticeable Differences (JNDs) thresholds. As example, Steele, James, Hori, Polacco and Yee (2014) measured oral viscosity discrimination ability for five non-Newtonian xanthan gum-thickened liquids in the nectar- and honey-thick range (51–1750 mPa s at 50/s), showing that there may be several increments of detectably different viscosity within the ranges currently proposed for nectar- and honey-thick liquids. Similar results were supported by the study of (Aktar, Chen, Ettelaie, & Holmes, 2015a) for a series of syrup solutions in the thin-range (1–50 mPa s at 50/s). A study investigating milk varying in level of starch thickener (non-Newtonian fluids) found individual differences in thickness JNDs for both younger and older adults, where the amount of thickener needed to detect an increase in thickness varied from 0.05 to 0.65% (Withers, Gosney, & Methven, 2013). This study additionally found that JNDs for mouth coating (investigating using milk varying in cream addition) varied substantially between individuals from 5 to 75%. As well, Camacho, Dop, de Graaf, and Stieger (2015) determined JNDs of oral thickness perception of Newtonian model stimuli (maltodextrin solutions). Moreover, the forced-choice staircase method was used to determine JND viscosity-differences thresholds for nine high-viscosity solutions (η = 4798–12260 cP) in a recent study of Miles, Wu, Kennedy, Zhao, and Simons (2022). The authors tested the hypothesis that tongue, and in particular filiform papillae, would be chiefly responsible for viscosity perception in the oral cavity, suggesting that viscosity

Table 2
Summary of different influencing factors on oral tactile sensitivity.

Author	Total subjects	Age (years)	Sex	Ethnicity	Test method	Effect of different factors				
						Age	Sex	FPD	Ethnicity	Other
Kawagishi et al., 2009	N = 329	Young adults (age 23–32, n = 269, mean age = 24.5); Senior subjects (age 66–91, n = 60, mean age = 80.5)	Young adults (F = 87, M = 182); Senior subjects (F = 51, M = 9)	–	Identify different shapes of polyethylene test pieces	Yes	No	–	–	
Steele et al., 2014	N = 78	Age < 40, n = 39, mean age = 26; Age > 60, n = 37, mean age = 70	–	–	Letter recognition test	Yes	–	–	–	Tongue strength: No
Shupe et al., 2018	N = 98	Young (age 20–25, n = 34); Middle (age 35–45, n = 31); Old (age > 62, n = 28)	Young (F = 22, M = 12); Middle (F = 18, M = 13); Old (F = 16, M = 12)	Young (White = 26, African American = 3, Asian/Pacific islander = 3, Latino = 2); Middle (White = 29, African American = 1, Asian/Pacific islander = 1); Old (White = 28)	Identify 3D printed shapes and confectionary letters	Yes	No	–	–	Dental status: Yes; Masticatory performance: No; Bite force sensitivity: No
Shupe et al., 2019	N = 117	Oral tactile sensitivity group: Low 25% (n = 21, mean age = 47.8); High 25% (n = 20, mean age = 37.1)	Oral tactile sensitivity group: Low 25% (F = 9, M = 12); High 25% (F = 10, M = 10)	–	Identify 3D printed shapes and confectionary letters	No	No	–	–	Several masticatory behaviours e.g. chewing pattern: Yes
Bangcuyo et al., 2017	N = 48	Age 18–59	F = 24, M = 24	–	Identify 3D printed shapes	Yes	No	Yes	–	
Appiani et al., 2020	N = 282	Children (n = 147, age 6–13); Parents (n = 65, age 32–58); Adults (n = 70, age 19–33)	Children (F = 73, M = 74); Parents (F = 50, M = 15); Adults (F = 37, M = 33)	–	Von Frey filaments and Gratings orientation task	No	Yes	–	–	
Lukasewycz et al., 2012	N = 98	Mother (n = 46, age 25–56, mean age = 39); Children (n = 52, age 7–10, mean age = 9)	Children (F = 31, M = 21)	Mother (White = 17, Black = 28, Hispanic = 1); Children (White = 14, Black = 32, Hispanic = 1, Mixed race/other = 5)	Modified letter-identification task	No	–	–	–	
Essick et al., 1999	N = 20	10 Men and boys (age 16.9–24.3; mean age = 21.5); 10 Women (age 20.3–23.7; mean age = 21.7)	F = 10, M = 10	–	Letter recognition test		No			
Michon et al., 2009	N = 274	Age > 20	F = 187, M = 87		Identify icing cake-type letters		Yes			
Essick et al., 2003	N = 83	Age 18–35, Asian (mean age = 21); Caucasian (mean age = 28)	Only females	Asian (n = 52); Caucasian (n = 31)	Letter recognition task	–	–	Yes	–	PROP: Yes
Nachtsheim et al., 2013	N = 116	Age 19–39	F = 84, M = 32	–	Von Frey filaments	–	–	No	–	
Zhou et al., 2020	N = 94	Age 18–70, mean age = 23.7	F = 64, M = 30	Caucasian (n = 58); Asian (n = 29); African (n = 7)	Von Frey filaments	–	–	Yes	–	
Komiyama et al., 2007	N = 88	Age 20–31	Belgian Caucasian (F = 22, M = 22); Japanese (F = 22, M = 22)	Belgian Caucasian (n = 44), Japanese (n = 44)	Semmes-Weinstein monofilaments	–	No	–	No	–
Ketel et al., 2022	N = 85	Dutch Caucasian (mean age = 22.8);	Dutch Caucasian (F = 29, M = 15); Chinese Asian (F = 30, M = 11)	Dutch Caucasian (n = 44); Chinese Asian (n = 41)	Von Frey monofilaments	–	–	No	No	

(continued on next page)

Table 2 (*continued*)

Author	Total subjects	Age (years)	Sex	Ethnicity	Test method	Effect of different factors				
						Age	Sex	FPD	Ethnicity	Other
		Chinese Asian (mean age = 24.5)								
Santagiuliana et al., 2019	N = 92	Dutch Caucasian (age 18–29, mean age = 21.4); Chinese Asian (age 21–27, mean age = 23.3)	Only females	Dutch Caucasian (n = 47); Chinese Asian (n = 45)	Von Frey monofilaments	–	–	–	No	
Cattaneo et al., 2020	N = 152	Age 18–55, Danish Caucasian (mean age = 29.8); Chinese Asian (mean age = 26.9)	Danish Caucasian (F = 52, M = 15); Chinese Asian (F = 56, M = 19)	Danish Caucasian (n = 77); Chinese Asian (n = 75)	Von Frey monofilaments	–	–	No	No	
Shinkai et al., 2004	N = 589	Diabetic subjects (mean age = 61.8); Nondiabetic subjects (mean age = 58.8)	Diabetic subjects (F = 48, M = 59); Nondiabetic subjects (F = 274, M = 208)	Diabetic subjects: Mexican American (n = 75), European American (n = 32); Nondiabetic subjects: Mexican American (n = 255), European American (n = 227);	Oral micro aesthesiometer	No	–	–	Yes	Diabetes: No
Perez et al., 2006	N = 33	Mean age = 35, Patients with middle ear surgery (n = 15); Healthy subjects (n = 18)	F = 19, M = 14	–	Semmes-Weinstein monofilaments; Static and moving 2-point discrimination	–	–	–	–	Middle ear surgery: Yes
Bogdanov et al., 2021	N = 89	Patients with subjective taste disturbance (n = 46, mean age = 60); Healthy subjects (n = 43, mean age = 55)	Patients with subjective taste disturbance (F = 25, M = 21); Healthy subjects (F = 23, M = 20)	–	Identifiy 3D-printed set of capitalized letters	–	–	–	–	Dysgeusia: Yes
Zhang et al., 2022	N = 54	Edentulous subjects (n = 18, mean age = 79), Age-matched dentulous subjects (n = 18, mean age = 77); Young healthy dentulous subjects (n = 18, mean age = 29)	Edentulous subjects (F = 10, M = 8); Age-matched dentulous subjects (F = 10, M = 8); Young healthy dentulous subjects (F = 10, M = 8)	–	Von Frey filaments	Yes	–	–	–	Dental loss: Yes
Lv et al., 2020	N = 20	Age 22–26, mean age = 20.5	F = 10, M = 10		Semmes-Weinstein filaments; Two-point discrimination	–	–	–	–	Tongue surface temperature: No

solutions is associated with filiform papillae length and density, but not with their diameter.

3. Factors influencing oral tactile sensitivity

As shown in Table 2, different factors may affect oral tactile sensitivity.

3.1. Effect of age

Generally speaking, the aging process of the human being is associated to a decline in orosensory functions, which can be a consequence of e.g. senescence of the sensory receptors systems and reductions of their neural systemic efficiency (Kremer, Mojet, & Kroeze, 2005). Kawagishi, Kou, Yoshino, Tanaka, and Masumi (2009) compared the stereognostic ability of the tongue between young adults (mean age: 24.5 years) and seniors (mean age: 80.5 years) by identifying differently shaped test pieces placed in the oral cavity; the seniors show decreased oral tactile ability compared with young adults. A similar finding was reported by Steele et al. (2014) that tactile sensitivity by Essick's letter recognition test does decline with advanced age in healthy adults (individuals under age 40 versus those over age 60). Shupe, Resmondo, and Luckett (2018) investigated oral tactile sensitivity in three age groups of adults (young: 20–25, middle: 35–45, old: over 62) through 3D printed shapes and gummy candy alphabet letters, and it was found that the older age group has an inferior oral sensitivity than the young and middle age groups. Bangcuyo and Simons (2017) tested lingual threshold sensitivity through a modified letter identification task, and also found that lingual tactile thresholds were significantly impacted by age groups; participants older than 40 years had higher thresholds than those in their 20s. These findings, however, contrast to the scientific evidence of differences in oral sensitivity across lifespan, or more specifically comparing children and adults. For example, the studies by Appiani et al. (2020) and Lukasewycz and Mennella (2012) did not find any age-related differences between children and adults. The Appiani study (2020) compared lingual tactile sensitivity between children and adults by using von Frey filaments and a gratings orientation test, while Lukasewyc study (2012) used a letter identification task between children and their mothers. The one exception in the Appiani study was for the thinnest Von Frey filament (F0.008), for which the performances of children aged 8 to 9 years were significantly better than the younger children and adults. Future studies may focus on how oral tactile sensitivity develops across lifespan.

3.2. Effect of sex

In the few studies specifically addressing sex differences in lingual mechanosensation, results are controversial. No differences between males and females were found by Shupe et al. (2018) in oral tactile sensitivity assessed by 3D printed shapes and gummy candy alphabet letters. Similarly, using the stereognostic letter identification task, tactile acuity was not affected by sex, although the study was underpowered due to a small sample size of only ten women and ten men (Essick et al., 1999). Another two studies also revealed no significant sex effect on the stereognostic ability assessed by identifying differently shaped test letters or pieces in the oral cavity (Bangcuyo & Simons, 2017; Kawagishi et al., 2009). However, in a study by Michon, O'sullivan, Delahunty, and Kerry (2009), females were found to have a higher ability to identify letter shapes in their mouth, though the choice of stimulus and the scoring procedure used to define sensitivity was dubious. More recently, Appiani et al. (2020) found significant sex differences in lingual tactile sensitivity only for the greatest grating size in the grating test, where adult women performed significantly less well than adult men; no sex differences were found in tactile sensitivity assessed by Von Frey filament. Further studies are needed to draw consistent conclusions regarding sex differences in oral tactile sensitivity.

3.3. Effect of fungiform papillae density (FPD)

In the anterior tongue, neuroanatomical studies have shown that somatosensory trigeminal neurons terminate as a network of fibres in the perigemmal tissue (des Gachons, Uchida, Bryant, Shima, Sperry, & Dankulich-Nagrudny, 2011; Suemune et al., 1992; Whitehead, Beeman, & Kinsella, 1985). Mechanical stimuli are likely to activate some receptors of the trigeminal nerve endings, which surround taste buds in the FP and terminate in the papilla apex (des Gachons, Uchida, Bryant, Shima, Sperry, & Dankulich-Nagrudny, 2011). It has been suggested that papillae density, and hence the number of the activated trigeminal fibres, underpins the intensity of trigeminally mediated qualities (Prescott, Soo, Campbell, & Roberts, 2004).

Previous studies have examined the relationship between fungiform papillae density (FPD) and oral tactile sensitivity. Several researchers found that lingual thresholds using the letter recognition task were significantly associated with FPD, such that higher densities resulted in greater tactile acuity (Bangcuyo & Simons, 2017; Essick et al., 2003). The positive correlation between FPD and tactile sensitivity was also observed in another study using point pressure by von Frey filament (0.008 g, $r = 0.41$) on the tongue surface (Zhou et al., 2020). However, Nachtsheim and Schlich (2013) found that FPD was not related to tactile sensitivity of pressure stimulated by von Frey filaments. The converse findings in tactile acuity by von Frey filaments might be attributed to stimulation areas in the tongue, e.g. whether touching the filaments to the fungiform papillae. The extent to which other modalities of lingual mechanosensitivity (e.g., a gratings orientation test) are influenced by FPD remains to be explored.

3.4. Effect of ethnicity

Research has also been conducted to evaluate ethnic differences of the oral tactile sensitivity. Komiyama, Kawara, and De Laat (2007) evaluated the ethnic differences between subjects in Belgium and in Japan, and no significant ethnic effects in the tactile sensitivity were found at the tongue tip stimulated by Semmes-Weinstein monofilament. Several other studies using von Frey/Semmes-Weinstein monofilaments found no significant ethnic effect in lingual tactile acuity between Asian Chinese and Caucasian Dutch participants (Ketel, de Wijk, de Graaf, & Stieger, 2022; Santagiuliana et al., 2019), nor between Asian Chinese and Caucasian Danish subjects (Cattaneo et al., 2020). Nevertheless, a ceiling effect was observed in Santagiuliana's work as most participants could detect the smallest stress used. Cattaneo et al. (2020) noted a trend that Asian Chinese subjects exhibited higher tactile acuity than Caucasian Danish subjects ($p = 0.08$). In a study conducted by Shinkai, Hatch, Cornell and Yeh (2004), European Americans demonstrated greater sensitivity compared with Mexican Americans ($p = 0.048$) on the soft palate when stimulated with Semmes-Weinstein filaments. More evidence is needed in the investigation of ethnicity and tactile acuity. If differences do exist between ethnic groups, then consideration needs to be made whether these stem from cultural gastronomic or genetic differences.

3.5. Effect of pathological changes

Along with the facial nerve damage, studies have shown that the somatosensory system may be disrupted after pathological changes. Perez et al. (2006) reported that the trigeminal sensitivity of the anterior tongue was significantly diminished in patients with clinical tongue symptoms after middle ear surgery, using the Semmes-Weinstein filament test and 2-point discrimination test. Schimmel, Voegeli, Duvernay, Leemann, and Muller (2017) found that intra oral tactile sensitivity on the contra-lesional side was significantly impaired in stroke patients compared to their healthy counterparts. Bogdanov et al. (2021) investigated the lingual tactile sensitivity of patients with dysgeusia based on 3D-printed letters sized from 2 to 8 mm, and observed that the patients needed significantly bigger letters to recognize them compared with controls. However, Shinkai et al. (2004) found that diabetic and nondiabetic subjects showed no significant differences in oral tactile sensitivity. It seems that it depends on whether such pathological changes cause impairment of nerves that result in tactile disturbance.

3.6. Effect of other physiological factors

Oral tactile sensitivity may also be related to other physiological measures, such as bite force, oral capacity, dental health, jaw muscle activity and saliva production. For example, Zhang et al. (2022) investigated the effect of ageing and tooth loss in tactile sensitivity measured by von Frey filaments and observed that both ageing and tooth loss can alter tactile and pain perception in the oral mucosa. Lv et al. (2020) tested the effect of tongue surface temperature on oral tactile sensitivity (Semmes-Weinstein monofilaments and two-point discrimination) and reported that both physical (hot/cold water) and chemical stimuli (capsaicin) fail to affect the oral tactile sensitivity. Steele et al. (2014) reported that that oral tactile sensitivity by letter recognition test does not appear to be related to tongue strength. Shupe et al. (2018) found that bite force sensitivity and masticatory performance were not correlated with oral tactile measures, demonstrating that bite force sensitivity measurements are likely measuring a different physiological ability from the lingual sensitivity and stereognosis measurements. Following the aforementioned study, Shupe, Wilson, and Luckett (2019) demonstrated that oral tactile sensitivity significantly associated with several masticatory behavior measurements including chewing pattern and overall number of chewing cycles. However, it should be noted that in that study only the data from top 25% and lowest 25% based on participants oral tactile sensitivity were used.

4. Association between oral tactile sensitivity and food perception, preference and choice

4.1. Relating oral tactile sensitivity to food texture perception and preference

Oral tactile sensitivity can be evaluated by a range of methods and devices, as discussed in section 2.

Certain studies show relationships between oral tactile sensitivity and sensory perception or preference of food texture, for example, a significantly positive relation was observed between oral tactile sensitivity (0.02 g Von Frey Filaments) and the ratings of biscuits hardness (Zhou et al., 2021), and high oral tactile sensitivity measured by two-point discrimination positively correlated to stronger abilities to identify particles in yoghurt (Olarte Mantilla et al., 2022). Most other studies fail to report significant correlations between oral tactile sensitivity and food texture perception or preference (Aktar et al., 2015a;b; Appiani et al., 2020; Furukawa, Ito, Tanaka, Ito, & Hattori, 2019; Lv et al., 2020; Shupe et al., 2019). For instance, Aktar et al. (2015a;b) examined tactile sensitivity (using von Frey filaments) and the discrimination of viscosity in syrup samples by means of just-noticeable-difference (JND) thresholds, reporting that the capability to discriminate sensory attributes (i.e., viscosity, firmness, and elasticity) are seldom linked to an individual's tactile sensitivity. The authors suggested that such results are somewhat reasonable because viscosity sensation is a dynamic process, hence touch sensitivity alone may have very limited relevance to viscosity detection. It has been suggested that food texture preferences are more influenced by factors such as culture and experience but are little influenced by one's oral tactile sensitivity (Aktar et al., 2015a; Liu et al., 2021). However, it is worthwhile noting that the cited studies measured tactile detection or recognition thresholds which may not fully reflect the real perception of food texture; they did not directly measure sensory sensitivity to texture presented by real products. Texture/mouthfeel perception from a food results from the combination of the tactile inputs both from the tongue and the soft palate (Engelen & Van Der Bilt, 2008). However, von Frey filament or 2-point discrimination test can only stimulate a very small area of the tongue which cannot reflect the tactile sensitivity in the whole mouth. Another important issue to consider is the part of the oral cavity assessed. Breen et al. (2019) observed a significant relationship between chocolate particle-size discrimination and pressure point sensitivity on the centre tongue, though a similar relationship was not seen for data from the lateral edge of the tongue. Their study results suggest that the relationship between texture perception and oral somatosensory acuity may depend on the stimulation part in the tongue. This is supported by a more recent study showing that while tactile sensitivity of the tip of the tongue (first one cm) did not relate with ability to detect particles, the sensitivity of the mid-section of the tongue (~second cm) related closely with particle detection in yoghurt samples (Olarte Mantilla et al., 2022). Moreover, the methodology used to assess oral tactile sensitivity (section 2), the reliability of testing techniques in different laboratories across countries should also be considered. Further investigations are required which combine different methods to assess tactile sensitivity in real food products when correlating to texture perception and preference.

4.2. Relating oral texture sensitivity to food texture perception and preference

Oral texture perception sensitivity can be evaluated using discrimination tests for specific aspects of texture, by using appropriate test foods (Furukawa et al., 2019). It has been suggested that food perception and preference might be more related to these discrimination abilities compared to lingual tactile acuity, although the relation between tactile sensitivity and acceptance of food is hardly studied in adults. Kim and Vickers (2020) evaluated individuals' liking of food texture and its relation to particle size sensitivity, and they observed that liking of cooling, gelatinous, and waxy texture increased with higher particle size sensitivity; liking of crystalline, doughy, rigid, and soft texture decreased with higher particle size sensitivity. Olarte Mantilla, Shewan, Shingleton, Stokes, and Smyth (2020) also demonstrated that consumer acceptance of yoghurt is impacted by their ability to detect particles. Puleo et al. (2019) investigated individual sensitivity to discrimination of different levels of graininess in cocoa-based creams and its relationship with liking. Subjects were clustered into three groups in terms of perceived graininess (high, moderate and low sensitivity). The results showed a significant difference between the three groups in terms of perceived graininess, but only small differences were found in terms of liking scores. Indeed, all the samples were equally liked for both the moderate and low sensitivity groups, whereas a significant trend was observed for the highly sensitive subjects who liked the most refined samples more. In another study, it was found that individuals with different levels of hardness sensitivity differed in hardness perception and liking of jellies (Puleo, Valentino, Masi, & Di Monaco, 2021). The studies demonstrate that an individual's ability to detect texture changes, such as graininess, particle size and hardness, may play an important role in food perception or preference.

4.3. Relating oral texture sensitivity and food choice, satiety and intake

Besides food perception and preference, individual's oral texture sensitivity can also affect food choice, satiety and intake. Puleo, Masi, Cavella, and Di Monaco (2021) used chocolate creams with different levels of flowability, and found that the sensitivity to flowability significantly affected individual choice of foods and liking of chocolate creams. Olarte Mantilla et al. (2020) reported that consumers who were 'non-detectors' of particles in yoghurt rated food choice factors 'natural content' and 'familiarity' as significantly more important to them, and they were more likely to be food neophobic. Pellegrino, Jones, Shupe, and Luckett (2019) provided evidence that the assessment of caloric density, satiety, and satiation are linked to specific sensory modalities, such as the ability to detect viscosity in milk samples of varying viscosity. Several other studies reported that an increase in touch sensitivity has been associated with increased picky eating and reduced food intake in children (Farrow & Coulthard, 2012; Nederkoorn, Jansen, & Havermans, 2015; Smith, Roux, Naidoo, & Venter, 2005) and adults (Nederkoorn, Houben, & Havermans, 2019). However, it should be noted that in the aforementioned studies, touch sensitivity in children was assessed by questionnaire rather than methods discussed in section 2. Despite of the paucity of literature, the findings stress the importance of gaining more knowledge about the role of oral texture sensitivity in food choice and intake.

5. Conclusion and perspectives

This work has reviewed methods used to test oral tactile sensitivity, including the two-point discrimination task, grating orientation task, letter-identification task, and pressure sensitivity by filaments and aesthesiometers. These methods normally represent a single dimension of texture perception and thus are not directly linked to perception of other texture dimensions. The discrimination sensitivity to specific texture attributes seems more likely to predict texture perception and/or

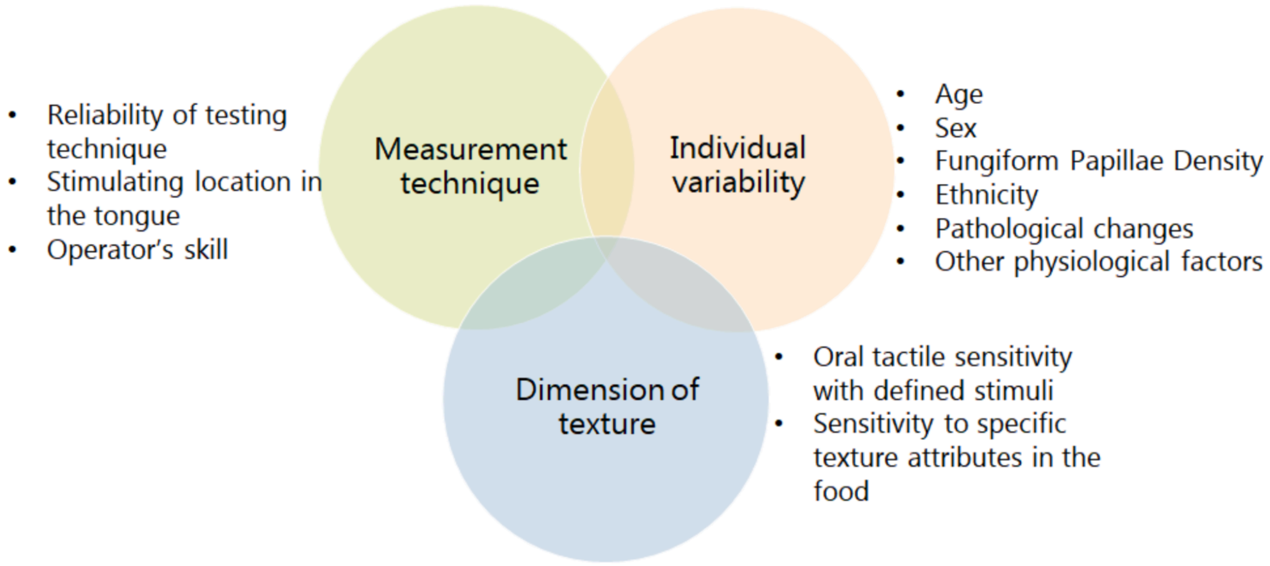

Fig. 1. Factors contributing to variability in oral tactile sensitivity and its relation to texture perception and preference.

preference of specific foods. As shown in Fig. 1, several factors such as age, sex, FPD (fungiform papillae density), ethnicity, pathological changes and other physiological measures such as dental loss may affect oral tactile acuity. However, evidence of these effects on oral tactile acuity is not consistent within the scientific literature. The methodology used to assess oral tactile sensitivity, the reliability of testing techniques in different laboratories across countries, the area of the tongue stimulated, and the operator's skill must be considered when investigating the influential factors in oral tactile acuity. Future studies may consider comparing different testing techniques and monitoring the repeatability of the operators over time. The relationship between discrimination tests of specific texture attributes and texture preference are also recommended in order to examine the nature of texture perception and preference. Having a meaningful and reliable texture discrimination and preference indicator is critically important for the food industry in the development and optimization of new food products, and in particular to design foods for individuals with special needs, such as elderly people and dysphagic patients.

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