**The role of texture in the palatability and safety of foods**

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1. Introduction

2. Palatability

2.1 Palatability: definition and quantification 9

2.2 Terms of texture 14

2.3 Significance of texture 19

2.3.1 Significance of texture 19

2.3.2 Crispness 22

2.3.3 Creaminess 23

2.3.4 Juiciness 29

3. Texture sensation

3.1 Physiological bases of sensation 30

3.1.1 Sensory Receptors 32

3.1.2 Teeth 34

3.1.3 Muscle activity 35

3.1.4 Tongue 37

3.1.5 Saliva 39

3.2 Nervous systems 41

3.2.1 Neurons responding stimuli  41

3.2.2 fMRI 44

3.3 Instrumental simulation of mastication 48

3.4 Virtual reality approach

3.4.1 Thermal 52

3.4.2 Visual 53

3.4.3 Auditory 54

4. Food oral processing 56

4.1 Breakdown process of ingested foods 57

4.1.1 Selection and breakage 60

4.1.2 Matrix formulation of breakdown process 63

4.2 Particle size of boluses 64

4.3 Granulationand bolus formation 66

4.4 Swallowing 69

5. Individual difference in oral processing 72

6. Texture perception in liquids and solids

6.1. Texture perception in liquids 74

6.2. Texture perception in solids 78

6.3. Chewing velocity decreases with increasing firmness ? 79

6.4. Some problems in the sensory evaluation 83

7. Conclusion 84

Acknowledgements 85

References 85

1. **Introduction**

We feel happy when we eat palatable foods, and eating pleasure is most lasting than other pleasures even when we get older (Brillat-Savarin, 1848). In more modern words: palatable food increases the activity of dopamine cells involved in the rewarding processes (Volkov, Wang, & Baler, 2011).

In some developed countries, people tend to eat too much, and the obesity is becoming a serious problem while on the other hand many people die because of the lack of foods. How we can quantify the palatability is an important problem to control the body weight, and to reduce the food loss which is also a serious problem from the viewpoint of sustainability and environmental protection (Alvarez de los Mozos, Badurdeen, & Dossou, 2020).

To discuss the palatability, it is important to know the cultural difference in the human attitude to eating and foods (Fischler, 2011). Attitude to eating and foods in four countries USA, France, Flemish Belgium and Japan were examined by analyzing the questionnaire consisting of 7 factors, 1) Eating diet modified to be healthier, 2) Concern for healthiness of food habits of self and others, 3) Extent of worry about fattening effects of food as opposed to savoring of food (worry about weight), 4) Diet-health link, perceived importance of diet for health, 5) The importance of food in life, 6) Culinary as opposed to nutritional associations to food, 7) Self-perception as a healthy eater (Rozin, Fischler, Imada, Sarubin, & Wrzesniewski, 1999). Results of questionnaire were found as follows:

1) The consumption of reduced fat/salt foods was found higher in female than in male in all four countries, and American females take such foods at least a few times a week, and French and Belgian males were found to take least. 2) French and Belgian males indicated little thinking about long-term health consequences, while Japanese students and adult females as well as American males and females showed the opposite tendency. 3) Highest worry about fattening effects of food was found highest again in American adult and student females while the lowest in Japanese student males. It was found that at least half of the subjects associate chocolate cake more with celebration than guilt. However, the two groups that report guilt most frequently were the American student females (39%) and the Japanese adult females (50%). 4) The belief of the diet-health link was found strongest in Japanese adult females and weakest in French adult males but the difference was not so remarkable. People in all four countries were found to believe the link between the diet and health, and the belief was found slightly stronger in females than in males. 5) The importance of food was found the highest in French people and lowest in American student females. While 70–90% of French and Belgians preferred the gourmet hotel, only 27–57% of Americans did. The Japanese lied in between. 6) It was reported that “Females showed fewer culinary associations”. However, for this factor 6), the questionnaire did not seem to be reasonable. The meaning of the question “choosing the word that you think is most different from the other two: carbohydrate, bread, butter”. From which viewpoint the choice should be made is not evident. Even if the respondent is interested in culinary aspect, he/she might know that the main ingredient of bread is carbohydrate. 7) Americans considered themselves not the healthy eater, only 23–45% of Americans claimed to be healthy eaters, in comparison to 47–60% for the Japanese, 63–77% for the Belgians and 69–82% for the French. Summarizing these results Rozin et al. (1999) noticed the more positive attitude to food in French and Belgians, and also in males than in females in all the countries. As for body mass index (BMI), Americans showed the highest mean BMI (23.2), followed by the French (22.2), Japanese (21.4) and Belgians (21.2). Country and gender effects for BMI were found highly significant. Although Americans worry most about their diet, modify their diet to a healthier direction, they think themselves not healthy eaters. Although the study by Rozin et al. (1999) was limited to prosperous and developed countries, this was the first detailed study on the attitudes to eating and foods, which triggered the subsequent studies. As these authors commented, the relation between the pleasure experiences and good health, and the stress and poor health must be further examined. As was pointed out, the difference in dominant religion, Catholicism in France, Protestantism in the U.S.A. might explain partially the difference in the attitudes. Americans may think their responsibility to maintain the health and body shape more than the French. People who consume “junk” foods were considered to be morally inferior to those who consume principally fruits, grains and vegetables (Stein & Nemeroff, 1995).

French are known to eat a highly palatable diet, containing more total fat and saturated fat than the American diet (Drewnowski et al.,1996), and consume less of fat-reduced foods, the mortality rate from heart disease was reported substantially lower among the French than Americans. While this so-called French paradox was explained by higher intake of wine by French than Americans, another important reason for this paradox was examined (Rozin, Kabnick, Pete, Fischler & Shields, 2003). The portion size of served foods was found smaller in France than in USA by examining the actual portion sizes in restaurants (the same chain restaurants or similar type restaurants) in Paris and in Philadelphia, the portion sizes described in restaurant guides, and portion sizes described in cookbooks (Rozin et al, 2003). It was also found that time spent for meals was longer in France than in USA, for example, the mean time spent eating and sitting in McDonald’s at the same time of the year at lunchtime, was 22.2 min in France and 14.4 min in USA.

As shown in the preference of energy-dense foods, humans have the innate favor during the long history of the evolution. There has been an intuitive belief that unhealthy foods are tasty (Unhealthy=Tasty intuition, “UTI”), which was examined in more detail (Raghunathan, Naylor, & Hoyer, 2006). It was shown that consumers tended to consume more unhealthy foods because they assumed that unhealthy foods are more tasty. Then the belief in UTI has been found as a kind of trade-off. To which extent this UTI affects the taste inference was examined by a psychological experiment, implicit association test (IAT), frequently used by psychologists (Greenwald, McGhee, & Schwartz, 1998; Greenwald, Nosek, & Banaji, 2003). It was assumed in IAT that it should be easier for subjects to judge the stimuli that were strongly associated than to stimuli that were weakly associated in memory. Thus, the response time was expected shorter for the former than for the latter.

In the first experiment (Raghunathan et al., 2006) categorization tasks for (1) pictures of unhealthy foods, (2) pictures of healthy foods, (3) words associated with the tastiness or enjoyment of food (e.g., tasty, delicious), and (4) words associated with the lack of taste or enjoyment (e.g., flavorless, unpalatable) were performed by subjects. When the stimuli to be categorized were arranged congruently (i.e., when subjects paired unhealthy foods with words associated with tastiness and enjoyment), the response time was found shorter than in the incongruent combination (healthy foods with words associated with tastiness and enjoyment). UTI was also found using cracker containing different fat, or mango lassi.

Since it was expected that the strength of UTI was different in persons who were health conscious or not, Mai & Hoffmann (2015) examined the influencing role of health consciousness.

These authors thought that health consciousness alone cannot explain the implication of UTI affecting the choice between the short term indulgence and the long term health considerations. They showed that persons having a stronger belief in UTI consumed a smaller amount of healthy foods, which was interpreted that healthy foods = non-tasty foods were less attractive, and the tastiness was the main driver for the consumption. Although the health consciousness diminished the explicit belief in UTI, and reduced the BMI, the implicit associations of taste and health could not be changed. Then, yogurts with different contents of sugar and fat, which were labelled on the cup for the degustation, were evaluated by respondents. The experience (tastiness) and the credence qualities (healthiness) were assessed by different modes of human information processing, i.e. different human senses. The effect of implicitly induced taste perceptions on food decision was found far stronger than that of healthiness expectations. From these results, the authors proposed the close collaboration among policy makers, food companies and consumers realizing the supply of healthy = tasty foods rather than only to trying to raise the healthiness consciousness and suppress the stable lay theories (UTI).

Since the psychological attitude maybe different in different countries as was demonstrated in Rozin et al. (1999), the concept of UTI was re-examined by conducting a similar experimental procedure in France (Werle, Trendel & Ardito, 2013), and compared with USA results by Raghunathan et al. (2006). French subjects showed an opposite trend: healthy = tasty! Werle et al. (2013) attributed this to the difference in the attitude to eating and foods in USA ad in France. While foods are seen from utilitarian and nutritional point of view in USA, foods are more associated with pleasure, social interaction, culinary and quality in France (Rozin, Kabnick, Pete, Fischler & Shields, 2003). Portion size, time dedicated to eating and snacking are also different but this difference was thought to be the consequence of the above-mentioned difference. Results of IAT by French subjects were opposite to those in USA, i.e., healthy = tasty although the tendency was found weaker for the restrained eaters, which was interpreted that the guilt associated with food consumption could be one of the keys to explain the inter-cultural differences identified in Werle et al. (2013).

Since the globalization and the increase in travelers may mitigate the difference in food culture and the food attitude in different countries, and the physical activities are also an important factor for the obesity, the comparative studies of food attitude and physical activities in four countries USA, UK, France and Belgium were done using the same sampling method and questions (Cooremans, Geuens, & Pandelaere, 2017). Participants were about 476 in Belgium and 650 in USA. France and UK were in between. The number of over weight (BMI>25) participants was highest in USA (61 %), lowest in France (36.6%), and those of UK and Belgium were in between, and this was in accordance with the data given by WHO. In food choices from 20 pairs of relatively healthy and unhealthy food item, such as salad vs. pizza, granola bar vs. brownie, the Belgians chose the highest amount of healthy options (57%). People from the UK chose more healthy food options than people from US (52%) and the France. The difference among countries was much smaller than in the previous reports (Rozin et al., 1999). No significant between-country differences were found in the belief of UTI (health and taste are inversely related). This was different from the results reported by Raghunathan et al. in 2006.

Since Asian countries were not included in these studies on UTI, recent study recruited more than 700 respondents from Australia, Singapore, India and Germany (Briers, Huh, Chan & Mukhopadhyay, 2020). These authors emphasized the necessity to distinguish implicit UTI which was examined by IAT (implicit association test) and explicit UTI which was referred to “UTI belief”. Respondents were guided to indicate how tasty and how healthy for 20 commonly consumed foods (apple, banana, raisins, orange, tomato, cucumber, carrot, broccoli, McDonald's burger, McDonald's French fries, KFC fried chicken, Pringle's potato chips, milk chocolate, vanilla ice cream, chocolate chip cookies, brownie, Coca-Cola, orange juice, Kellogg's corn flakes, and ketchup). After indicating the tastiness and healthiness of each food item, participants assessed the strength of the UTI belief: “There is no way to make food healthier without sacrificing taste,” “Things that are good for me rarely taste good,” and “There is usually a trade-off between healthiness and tastiness of food.” The strength of UTI belief was found in the order India >Hong Kong> UK>Australia> Germany, however, the difference in UTI belief across countries was found small. The relation between UTI belief and BMI was found weaker in Asia than in Europe, which was found consistent with the previous reports that main driver governing the food choice was taste in Europe, and health in Asia (Januszewska et al., 2011; Prescott et al., 2002). Therefore, the pleasure-oriented approach that emphasizes taste might be more effective to reduce BMI in Western countries, which is consistent with recent finding that vegetable intake was increased by emphasizing their tasty and enjoyable attributes (Turnwald, Bertoldo, Perry, Policastro, Timmons, Bosso, C., et al., 2019). In Asian countries, a more cognitive approach that focuses on health was expected to work better. Briers, et al. (2020) also found that the consumption of fruit did not lead to a decrease in body weight though that of vegetables worked. Many respondents might think fruit juice as fruit category, but fruit juice contained sucrose and no dietary fiber, different from vegetables.

Appearance, texture, sound, temperature, and color may be called physical taste. After 10 years of Szczesniak's examination of the importance of food attributes in the USA (Szczesniak, 1963a, b), which showed that texture is equally important to flavor, Matsumoto and Matsumoto (1977) carried out similar examinations choosing different common foods including Japanese traditional dishes, and reached the same conclusion. In addition, it was shown that the texture is more important in solid foods than in liquid foods; the palatability of cooked rice, noodles and breads which are eaten as staple foods in Japan and have no strong chemical taste and odor, is mainly determined by the texture (Nishinari, 2004).

The worldwide recognition of the importance of the food texture drove scientists to organize the First Food Summit in1999 in Wageningen. Forty-five scientists from 10 countries, oral physiologists, dentists, food scientists, psychologists participated (Hamer & de Wijk, 2002).

Texture is attracting in relation with obesity. The prevalence of obesity has surpassed the issue of undernutrition (de Graaf, 2020; WHO, 2022). Globally, more than 820 million people remain undernourished, whereas more than 2 billion people are overweight or obese (Willett et al. 2019). Many papers have reported that the rate of liquid foods intake is much faster than that of solid foods, also softer solid foods (cake and minced meat etc) than harder foods to take the same energy (calorie), and that the overeating occurs more frequently in fast eating than in slow eating (de Graaf, 2020). Hogenkamp, Stafleu, Mars, Brunstrom, & de Graaf (2011) examined the effect of the texture (liquid or semi-solid), flavor and mode of consumption on the expected satiation. Served test foods were yogurt and custard, lemon and meringue flavored custards with different textures, chocolate milk and chocolate custard consumed with either a straw (faster) or a spoon (slower). It was observed that variation in texture caused much stronger effects in expected satiation than variations in flavors.

Texture has been attracting also from the viewpoint of safe ingestion of foods. Much effort to reduce the incidence of food accidents caused by choking and aspiration has been made. The Japanese Society of Mastication Science and Health Promotion was established in 1991 by Kinjiro Kubota who recognized the necessity of the collaboration between oral physiology, dentistry, food, nutrition, and cookery science. Kubota (2000), based on the comparison of phylo- and ontogenic development of humans, proposed that vigorous mastication from infancy onwards will enable humans to enjoy healthy and robust old age. He had reported in collaboration with Momose that vigorous gum-chewing increased human cerebral blood flow in the primary sensorimotor areas by 25-28%, the supplementary motor area and insulae by 9-17%, and the cerebellum and striatum by 8-11% from the positron-emission tomography (PET)-autoradiography. It was pointed out that the number of children who don’t take breakfast, or who prefers only beverages or soft foods which can be swallowed without chewing, causing the lack of space in the oral cavity to have normal number of teeth (28 in adults), and resulting in the snaggleteeth. A recent systematic review pointed out the between mastication and cognitive impairment including dementia among elderly people (Tada & Miura, 2017).

Chewing time timetimetimetime

The effect of low mastication ability on the impaired cognitive function was studied using juvenile mice fed with soft diet (powder) requiring less masticatory stimuli than normal diet (chow pellets) (Fukushima-Nakayama, Ono, Hayashi, Inoue, Wake, Ono et al., 2017). It was found that reduced mastication led to the decrease in the number of neurons. Both synapse formation and neuronal activity were also found to decrease with the reduced mastication. Since the neuronal activity is known strongly related to synapse formation, the decrease in synapses in mice with reduced masticatory stimuli was thought to be induced by the decreased neuronal activity (Fukushima-Nakayama et al., 2017). A concise review on this problem was recently published (Krishnamoorthy, Narayana & Balkrishanan, 2018).

Shigeru Saito examined the number of chewing in meals of which recipes in each age from the 2nd century to the present were reproduced based on the historical archives. The number of chewing and the time for one meal were found to have reduced from 3990 and 51 min to 620 and 11min, respectively. A motto derived from this study *Himiko no ha ga iize* is popularized widely in Japan. [www.tokachi-doctor.com/himiko](http://www.tokachi-doctor.com/himiko), 29March2023accessed [www.excite.co.jp/news/article/CocokaraNext\_32732](http://www.excite.co.jp/news/article/CocokaraNext_32732), 29March2023accessed

<http://www6.plala.or.jp/saitou3/hanohanasi/himiko/>, 29March2023accessed

The significance of the mastication was explained concisely by Yoshiaki Yamada in the following website of Japanese Society of Mastication Science and Health Promotion

<http://sosyaku.umin.jp/info/file/info01.pdf>, 18 April 2023 accessed

Table 1 Evolution of chewing time and meal time in Japan (Saito)

The main goal of mastication is to break the food into smaller fragments, and agglomerate

them into a bolus(a rounded and cohesive mass) which can be safely swallowed through esophagus to be digested and absorbed. Through this process, the safety is assured and at the same time during the mastication, humans experience the pleasure to eat when the food is palatable. Then, the 1st International conference on mastication was held in Yokohama in 2002 (Nishinari, 2004).

In 2010, Food Oral Processing conference was held in Leeds, and the succeeding conference of the same name have been organized every two years (Wolf, B., Fisk, Rosenthal, A., Chen, J., 2019). In spite of the difficulty caused by covid-19, the 6th FOP was held in Valencia, Spain in 2021.

In the present paper, the definition and quantification of palatability is discussed first, and then the texture the important elements of the palatability is discussed. Breakdown process is discussed based on some models, and the size and size distribution of food fragment, and the bolus formation are discussed. Since texture can be evaluated only by humans but sensory evaluation takes a time and costly and difficult to get the reproducibility thus instrumental measurements have been developed. Physiological knowledge is indispensable to perform an instrumental measurement and to design the instrument. Thus, the basic concepts of oral organs, teeth, tongue, muscles of mastication and saliva are described. Since the palatability is judged in the brain, the transduction of signals received at receptors through nervous systems is also described.

1. **Palatability** 
   1. **Palatability: definition and quantification**

It has been known that fat is palatable and has high energy density, i.e. energy per unit mass is higher than carbohydrate or protein. Drenowski (1998) quantified this, and showed that energy-dense foods are palatable but not satiating, whereas foods with low energy density are more satiating but less palatable. Food industry has been struggling to create palatable foods with low energy density, especially with creamy texture, using polysaccharides or proteins to prevent the prevalence of obesity. From old days, humans seem to prefer to eat something different from what they ate yesterday or at previous meal time even though that was delicious and nutrient as Israelites complained: We remember the fish, which we did eat in Egypt freely; the cucumbers, and the melons, and the leeks, and the onions, and the garlic **(**Numbers 11:5), But now our soul is dried away: there is nothing at all, beside this manna, before our eyes (Numbers 11:6). Bourne (2002) cited this episode and interpreted that manna bored Israelites even though manna was delicious and nutrient, but poor in the variety of sensory attributes and he thought it was the monotonous texture which disgusted people. Many papers have been published on the effect of variety on the food intake (Wadhera & Capaldi-Phillips, 2014), and the visual cue especially color plays an important role to avoid the boredom (Piqueras-Fiszman & Spence, 2014).

When we think about the factors shaping attitudes and acceptance of food texture, extremely important are physiological factors that refer to the ability of the consumer to handle the food during consumption (Szczesniak, 2020). People want to be in full control of the food in their mouth and *feel* that textures that are not easily manageable can cause discomfort, choking, and gagging. Crisp, chewy foods can be grasped firmly with the teeth, chewed into small bits, and swallowed with ease. Stringy foods can catch in the teeth and throat, while sticky foods will adhere to the tongue, gums, and palate, causing unpleasant situations that often lead to social embarrassment. People also want to be in full control of the food on the plate and will reject items difficult to cut and manipulate with eating utensils. One notable exception is consumption of whole, raw oysters. Slimy and slippery, they are not chewed in the mouth but are allowed to slide down the throat in an almost uncontrollable manner. This is an acquired custom (incomprehensible to many, including this author) spurred by a snobbish desire of some people to belong to a “gourmet elite.” Another set of physiological factors affecting texture acceptance is the limited strength of our teeth and jaws (modern humans do not chew bones!) and the proneness to injury by sharp objects of the soft tissue in our mouth (Szczesniak, 2020). During the growth, preferred texture is changing. When the texture is found different from what was expected, it is generally avoided. The interaction with other food culture sometimes changes the preference. Szczesniak classifies the liked and disliked textural characteristics in USA as follows:

Table 2 Typical liked and disliked textural characteristics (Szczesniak, 2020).

Chen and Lolivret (2011) found that the difficulty in eating was correlated well with the residence time of the food in the mouth. They used 18 commercial liquid foods, from thin liquid such as milk, orange juice, yogurt drink (residence time ca 2 s) to thicker ones such as honey and peanut butter (residence time 7-8 s). It was found that the residence time was well correlated with viscosity. This may mean that food with shorter residence time, that is less viscous liquid is easier in oral processing and will be liked. Subjects in this examination was not old ;19 panellists aged between 21 years and 57 years (average 28.7 years) and of both genders (16 females and 3 males). This is consistent with the findings of Yoshimura, Kuwano, Funami, & Nishinari (2008) who found that younger panellists liked weaker binders for minced carrots. Since minced foods needed binders to agglomerate minced particles, Yoshimura et al (2008) compared the performance of the mixtures of xanthan (X) and high acyl gellan gum (G). While the time per one chew (chewing time / chewing number) was shorter for X alone and X/G =0.4/0.2 in younger panellists than in elder panellists, that time was found shorter for X/G =0.2/0.4 (the strongest binding performance) in elderly than in younger panellists. This was interpreted that the oral management ability was reduced in elderly, and thus they liked minced carrots well agglomerated by X/G mixtures. The preference of the texture is dependent on the oral management ability, nevertheless, some components of oral function can be improved through appropriate training (Iwasaki & Hirano, 2022).

Hayakawa et al (2014) tried to quantify the eating difficulty by sensory analyses of hydrocolloid gels with a wide range of textures. Panelists evaluated six texture attributes including firmness, cutting effort, elasticity, extensibility, adhesiveness, and melting rate in the mouth. It was concluded that resistance to fracture and stickiness and flexibility were critical determinants of eating difficulty based on a principal component analysis.

Since homogenized pastes were not liked by elderly who have the difficulty in mastication and deglutition, enzymatically softened foods were developed (Fujishima, Shigematsu, Kanazawa, Nishimura, Nagao, Otsuka, et al., 2018). Mechanical properties of homogeneous enzyme permeation -treated chicken breast were compared with those of normally cooked chicken breast, and it was found that the firmness reduced almost ten times while fibrous texture of chicken was maintained by enzymatic treatment (Takei, Hayashi, Umene, Narita, Kobayashi, Masunaga, 2015). Thus, the enzymatic softening of tough foods enjoyed great popularity by virtue of another advantage, a better appearance than a paste (Piqueras-Fiszman & Spence, 2014; Wadhera & Capaldi-Phillips, 2014) because you eat with your eyes first (Delwiche, 2012). This was in accordance with the enhancing effect of visual presentation on the saliva secretion and the appetite (Kamiya, Ota, Morishita, Sawa, & Kondo, 2015)，as will be discussed later in the section 3.4.2.Visual.

In addition to enzymatic softening of meat, creation of fibrous texture of meat analog based on soy protein has been done by extrusion cooking developed in 1980s (Nishinari, Fang, Nagano, Guo, & Wang, 2017). More recently, extrusion of soy protein, pea protein and gluten and their mixtures was developed to fabricate meat analog which has fibrous texture (Chiang, Loveday, Hardacre, Parker, 2019; Dekkers, Emin, Boom, & van der Goot, 2018; Grabowska, Zhu, Dekkers, De Ruijter, Gieteling, van der Goot, 2016).

While the inhomogeneity is reported to be useful to reduce the salt or sugar intake, phase separated mayonnaise is rejected because it is inhomogeneous. Thus, the inhomogeneity does not necessarily lead to palatability.

**Palatability affected by culture and social environments**

The liking and wanting were reported to be differentiated. The quantity of food consumed is dependent on the physiological demand. The natural tendency of liking sweet and weak salty taste has been understood by the requirement of energy and ionic balance. But this teleologic explanation sheds some light only on the physiological aspect. Irrespective of his/her religious belief, man shall not live on bread alone, and is conditioned from the birth (or even before birth in the womb as recent epigenetic study reported), and cultural, therefore, also economical, historical environment and personal experiences, and these may, in turn, affect the individual differences.

There have been many studies on the change of dietary patterns of Mexican immigrants in USA reporting that US-born and more-acculturated Mexican-Americans consume fewer traditionally-Mexican food items such as beans, tortillas, and fruits and vegetables, but consume more unhealthy foods and nutrients, including saturated fat, sugar, dessert and salty snacks, pizza and French fries than their foreign-born less-acculturated counterparts. As a result, the former population were found more obese than the latter (Batis, Hernandez-Barrera, Barquera, Rivera, & Popkin, 2011; Langellier, Brookmeyer, Wang, & Glik, 2014). Based on the 2005–2010 National Health and Nutrition Examination Survey (NHANES) (Mexican-American adult participants, including 1353 males and 1439 females), Langellier et al (2014) examined the relation between social, economical, cultural and food behaviors, and suggested that the language proficiency influenced the food choice and consumption.

A similar trend was also recognized in the rapid fall of the longevity ranking of Okinawa prefecture in Japan. An American journal *TIME* in a special issue “How to live to be 100” (2004) reported that Okinawa dietary pattern is healthy and assures the longevity: As for foods, less white rice, fatless meat, vegetables, soybeans (tofu) and fish and not overeating (80% fullness). Regular Exercise. As for psycho-social factors, ancestor worship, female priestesses, relatives network. It is desirable to have Reason for living, optimistic view of life (Masuzaki, 2012). Ironically, however, the so-called Okinawa crisis had already begun when the special issue of the *TIME* was published. The dietary pattern in Okinawa changed rapidly into American style, high fat and high calorie one. American fast food became popular in 1960’s in Okinawa ten years earlier than in mainland Japan. Thus, the top in longevity ranking fell to the 4th in 1995 and the 26th in 2000, the 25th in 2005.

The palatability in food has been studied from the viewpoint of the factors of food characteristics (physical and chemical) and the factors in human side, historical, geographical, cultural, physiological and psychological approach. Only a sight of a specific food drives a stimulus, for example, *umeboshi* (literally it means dried plum in Japanese), a Japanese traditional salted sour plum pickle, causes salivation. However, this sensation does not occur for persons who don’t know this food. Rolls raised an example of chocolate craver and non-craver, and showed that this can be understood more quantitatively by brain science. The sight of chocolate produced greater activation in chocolate cravers than noncravers at a specific site in the brain. For cravers versus noncravers, a combination of a picture of chocolate with chocolate in the mouth produced a greater effect than the sum of the components (i.e., supralinearity) in the medial orbitofrontal cortex and pregenual cingulate cortex (Rolls, 2020). Brain science approach has accumulated knowledge concerning the palatability through the change in electric activity potential and functional NMR (Rolls, 2016, 2019), which will be discussed later.

As exemplified in the large number of texture terms in Japan (Yoshikawa et al, 1973, Hayakawa et al, 2005; Nishinari et al, 2008), a wide range of texture are accepted and enjoyed in Japan which surprised Bourne (2002) during his stay. Most Japanese like *natto*, fermented soybeans covered with mucilage giving a sticky and slimy texture, generally disliked in European countries, and some people don’t like even in Japan, and is one of the most difficult foods for overseas visitors to appreciate (Nishinari and Ooizumi, 2020). Therefore, the discussion of the palatability can only be done taking into consideration this wide distribution of preference or liking. In the age of globalization, with increasing number of travelers, the food culture is changing faster than before. After the registration of *Washoku*, the Japanese traditional dietary cultures as a UNESCO Intangible Cultural Heritage in December 2013 https://ich.unesco.org/en/RL/washoku-traditional-dietary-cultures-of-the-japanese-notably-for-the-celebration-of-new-year-00869, some Japanese traditional cuisine, not only sushi, are now becoming popular in many countries (Nishinari, Fang, Tomczyńska-Mleko, & Mleko, 2016). This example shows a possibility of the change in palatability during comparatively a short time than in previous centuries. Although a creative chef aims to discover a new palatable cuisine which may be distant from the average, it is meaningful to examine the average liking score.

Since the palatability of foods is appreciated by all the five human senses, it is necessary to evaluate the properties detected by these senses. The pleasant feeling we get during eating originates from various aspects : the subjective aspect consists of physiological conditions (how hungry, state of oral cavity, etc), psychological conditions (eating with detestable persons, just after the death of parents or children or friends, just after a quarrel, etc), conceptual conditions (how one is brought up, prejudice or knowledge about the dish or raw materials, information given by media or rumor, etc), whilst the objective aspect consists of the food or dish itself, and originates from its physical properties and chemical properties (Bourne, 2002; Civille, 2011; Nishinari, 2011; Piqueras-Fiszman & Spence, 2016). Effects of food itself especially visual, auditory, olfactory, gustatory, tactile sensations induced by food on the palatability have been studied in food science, and humans have been vaguely aware of the effects of seemingly indirect psychological factors and recent research activities on multisensory perceptions now are shedding more light on this aspect (Spence, 2021).

Hedonic sensory evaluation to measure the palatability has been performed recruiting many subjects. Quantitative analysis for humans was examined by sensory evaluation, which is defined as a scientific discipline used to evoke, measure, analyze, and interpret reactions to stimuli perceived through the sense (ASTM E253-17) or science involved with the assessment of the organoleptic attributes of a product by the senses (ISO 5492). Quantitative descriptive analysis (QDA) has been used to characterize the perceived sensory attributes. Glossary commonly used is shown in a website:

https://www.sensorysociety.org/knowledge/sspwiki/Pages/Descriptive%20Analysis.aspx

The texture was defined by Szczesniak (1963) 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” or defined as “all the mechanical, geometrical and surface attributes of a product perceptible by means of mechanical, tactile and, where appropriate, visual and auditory receptors” (ISO 11036 1994). Since this is a perceived sensation and not a simple attribute but with multi-faceted aspects, there are so many instruments for texture measurements (Bourne, 2000). The texture becomes crucial especially when it does not satisfy the expectation such as stale bread or soggy crisps, but if it is within a right range, taste and aroma attract more attention. The texture plays an important role both in appreciation (liking) and recognition as will be discussed later.

While the texture profile Szczesniak proposed (2002) classified the sensory attributes into 1. Mechanical characteristics, 2. Geometrical characteristics, 3. Other characteristics (referring mainly to moisture and fat content of the food, Sherman (1969) emphasized the importance of temporal aspects since the sensation is changing before, during and after the ingestion of food in the mouth. The temporal aspect of the texture profile was incorporated in the mouth process model of Hutchings and Lillford (1988), where the time is the one important axis together with the structure axis and lubrication axis. Sensory evaluation methods such as time intensity (TI) and temporal dominance of sensations (TDS) analyzing the temporal aspects were developed (Lawless and Heymann, 2010a; Meilgaard, Civille and Carr, 2016; Rosenthal, 1999). Recently, the temporal drivers of liking (TDL) were introduced to analyze the temporal change of perceived sensory attributes (Thomas, Visalli, Cordelle, Schlich, 2015).

To understand the physiological mechanism which governs the food intake, animal studies have been done using rodents, mice and rats. Licking test is widely used because it is expected to give information on food palatability, incentive properties, and post-ingestive processes by analyzing the licking pattern (Naneix, Peters, McCutcheon, 2019). It is expected that the analysis of the total licking behavior not only the overall consumption or choice but also licking rate (6-7 Hz in rats and 8-10Hz in mice), now many lickings occur consecutively, interlick interval time, interrupted licking times, gives more information on eating behavior. According to Naneix et al. (2019), the reduction of the consumption is caused not only by the decrease in the preference in palatability but it is also influenced by the other internal processes (motivation, interindividual sensitivity for sweet taste, stress) and external parameters (experimental condition such as light/dark cycle, sweet taste concentration, bottle position etc.) (Scheggi et al., 2018).

Very few animal tests challenging the examination of the effect of texture using solid or semi-solid foods have been done to see the palatability through the licking tests and will be a future problem.

* 1. **Terms of texture**

Words to describe the texture have been studied by many workers. The importance of the texture in food has been recognized by pioneering works of Szczesniak and her coworkers based on word association technique used in psychology (Szczesniak, 1963; Szczesniak and Kleyn, 1963; Szczesniak, Brandt, Friedman, 1963). Her method was to show 74 different foods to 100 subjects working at General Food Co. Ltd. In USA asking to raise words (response) reminded by each food (stimulus). Attributes for each food were categorized into appearance, color, aroma, flavor, texture, and others, and it was found that texture was an important sensory attribute of foodstuffs and that in certain products it might be even more important than flavor. This was a groundbreaking finding because flavor had been believed to be a far more important attribute. This result stimulated food scientists, and Yoshikawa and his coworkers performed a similar association technique but they confined the association to texture excluding other attributes. They selected hundred different foods common in Japan: cooked rice, *mochi* (sticky rice cake), bread, Popcorn, noodle, custard, oat meal, spaghetti, mashed potato, boiled potato, *sato-imo* (yam), peanuts, salted beans, green peas, fermented soybeans (*natto*), red beans (azuki), bean curd (*tofu*), frozen bean-curd (*kori-dofu*), bean-curd refuse (*okara*), *konnyaku* (konjac gel), tofu (soybean curd), cabbage, tomato, spinach, asparagus, a type of mushroom (*shiitake*), scallion, lotus root, bamboo shoot, celery, osmund, *junsai* (sprout of [*Brasenia schreberi*](https://en.wikipedia.org/wiki/Brasenia_schreberi)), a type of pickle (*narazuke*), fresh tuna, scallops, salted salmon, surimi type (*kamaboko, chikuwa*), dried squid, mashed and seasoned fish (*denbu*), dried bonito, sea cucumber (*namako*), sea urchin, fresh cuttlefish, canned mackerel, ham, bacon, liver paste, roast pork, roast beef, roast chicken, boiled chicken, orange, peach, pear, watermelon, apple, grape, banana, raisin, shredded tangled kelp (*tororo-konbu*), *wakame* (seaweed, *Undaria pinnatifida*), laver (*nori*), cow milk, yoghurt, condensed milk, butter, peanut butter, cheese (Cheddar type processed), strawberry jam, biscuits, potato chips, rice cracker, millet and ricecake (*okoshi*), fried dough cake (*karinto*), bean jam bun (*manju*), sponge cake, cracknel, butter, honey, fried bean-curd (*aburage*), rock candy, caramel, drops, chocolate, boiled chestnut, marshmallow, chewing gum, ice cream, beer, cola, orange juice, cider (called so in Japan, non-alcoholic carbonated water), cocoa, blacktea, tomato ketchup, mayonnaise, corn soup, etc. Their subjects were 140 female students, and divided into two groups. Each group of 70 students were asked to respond to 50 foods. Although survey was conducted asking subjects to write down more than four suitable words related to texture for each food, 12600 responses were obtained (smaller than 100 × 140 = 14000) because some students could not get suitable words within a limited time of 40 min. The median frequency of mention per subject of a descriptive word for texture was 3.5. Since words which appeared only once seemed to be peculiar, they were omitted. Then, the median frequency 7 was obtained. Obtained words were hard, soft, juicy, chewy, greasy, slippery, creamy, *kori-kori* (crisp), *kari-kari* (crunchy), brittle, *torori-torori* (melting), *nuru-nuru* (slimy), not chewy, chilled, *pari-pari* (crispy), *para-para* (sprinkling) ,,,, and the authors noticed that frequently mentioned words were used in association with many foods, and many onomatopoeic words were found in Japan than in USA. It was thought to be related to the insufficient vocabulary or limited ability of the Japanese language in the young subjects. Although onomatopoeic words became used later in manga and animation, these words were thought to be low rank words in spite of some exceptions used by beloved poets and artists. Each food has a wide spectrum of nuances which cannot be described by only one word. A commonly used word can describe only one aspect of the rich spectrum.

Forty years later of Yoshikawa’s group (1970), Hayakawa and her coworkers (2005, 2006, 2007) re-examined the texture terms and found the general similar tendency that many onomatopoeic words were used as had been found by Yoshikawa and his coworkers. However, accompanying the change in the selection of foods, the texture terms were found also changed. They noticed that among the most frequently used thirty texture terms, only four onomatopoeic words, *shittori, kounyatt, mosomoso,* and *hukkura* were found (Hayakawa et al., 2018). One reason for this difference is that their survey was done collecting the data from 16 texture researchers and not from general public or from students. Most professionals or intellectuals seemed to think that the usage of the onomatopoeic words originated from the poor ability of the language of the people although they accept or praise some onomatopoeic words created by poets or artists. Since it is impossible to represent all the aspects/nuances of any matter, any word or sentence cannot grasp all the aspects/nuances.

Some widely known cartoon (*manga*) for foods became popular and words in *Oishinbo* (a carton created by Tetsu Kariya and Akira Hanasaki) were used as a corpus by some recent studies. Recently, words in foods were analyzed by linguists/information technologists. Onomatopoeic food descriptive words were classified based mainly on the collocation which indicates the appearance of one word together with another word (Kato, Fukazawa, Sanada, and Mori, 2014). This concept of the analysis of texture terms is not so different from that used by Yoshikawa et al. (1971) but the recent development of computer technology made it possible to process big data.

In the past two decades, the texture studies have advanced extensively based on the developed new techniques quantifying the physical and physiological behaviors in the oral cavity and also the brain science. As symbolized in a short phrase, “From tastes good to mouth-feels good” (Chen, 2020), the more comprehensive and total evaluation of foods, the texture in relation with palatability, safety, and digestion and absorption have been attracting much more attention. Recently, the texture characteristics of world foods were reported by texture scientists of more than 20 countries (Nishinari, 2020), and it was shown that texture plays an important role. Since it is convenient to arrange terms on the wheel for communication as has been done for whisky, wine and beer, mouthfeel wheel for medical nutrition products was proposed recently beccause it is believed to be convenient for communication (van der Stelt, Mehring, Corbier, van Eijnatten, Withers, 2020). (Fig.1).

Figure 1. A ’Mouthfeel Wheel’ showing a hierarchical representation of umbrella terms and mouthfeel attributes that can be used to describe the mouthfeel characteristics of medical nutrition products (van der Stelt, Mehring, Corbier, van Eijnattena, Withers, 2020).

The term cohesiveness has sometimes been used not in a correct sense and was proposed to be corrected (Hadde, Cichero, Zhao, Chen, & Chen, 2019; Nishinari, Fang, Rosenthal, 2019; Nishinari, Kohyama, Kumagai, Funami, and Bourne, 2013; Nishinari, Turcanu, Nakauma, and Fang, 2019). Recently, Rosenthal and Thompson (2021) re-examined the significance of cohesiveness based on the frequency of collocation.

Since the generation of lexicons consisting of standardized and descriptive terms need trained panel, and many of man-hours spent tasting, mouthfeeling and discussing samples, natural language processing (NLP) is becoming used by computer technology (Hamilton & Lahne, 2020). The analysis of larger volumes of free text available on website can be done by NLP tools to get flavor wheels or dendrograms automatically. In the NLP procedure, automatically collected words were cleaned, and analyzed by combining or removing suffixes, and disambiguated. Linguistic researchers are moving towards machine learning rather than using dictionaries, rules, and algorithms (Bates, 1995; Hamilton et al., 2020).

Texture terms for sensory evaluation are usually discussed within a panel in mother language, for example, French in French speaking area (Lenfant, Loret, Pineau, Hartmann, & Martin, 2009), Dutch in Dutch speaking area (Liu, Stieger, van der Linden & van de Velde, 2015; Oppermann, Piqueras-Fiszman, de Graaf, Scholten & Stieger, 2016) and Japanese in Japanese speaking area (Taniguchi, Harashima, Ishihara, Ushio, & Akiyama, 2021). As was mentioned above and reconfirmed later again (Nishinari, Hayakawa, Xia, Huang, Meullenet, Sieffermann, 2008), onomatopoeic words are frequently used in Japan both in food related area (Hayakawa et al, 2005) and cosmetic area (Taniguchi et al, 2021). Five words selected to describe tactile sensation of skin-care materials were all onomatopoeic; *nuru-nuru* (slimy), *gishi-gishi* (squeaky), *beta-beta* (sticky), *shittori* (moist), and *sara-sara* (smooth) (Taniguchi et al, 2021), while eight selected French (English) words, *dur* (hard), *craquant* (crackly), *croutiallant* (crisp), *friable* (brittle), *léger* (light), *collant* (sticky), *granuleux* (gritty), *sec* (dry) to describe the texture of breakfast cereals (Lenfant et al., 2009) were not onomatopoeic.

Vickers (1984) noticed that the very descriptors “crisp” and “crunchy” differed in pitch. The vowel sound of the “i” in “crisp” is higher pitched than the sound of the “u”in “crunch” (Marks, 1975). The “sp” ending of crisp is also higher pitched than the “ch’ ending to the term crunch. Thus, she thought that the sounds of the words themselves conveyed part of their meaning. This concept affirming that there is a relation between the word and the sound has been called sound symbolism. Although Saussure’s idea that the language is a system of signs which are arbitrary (Sausssure, 1959; Hutton, 1989) has been influential, some linguists pointed out the existence of some relation between the words (signs) and things. Even today, some are supporters and the others are opponents of Saussure who denied inherent or natural relation between the sign and its meaning.

The synesthesia - the translation of attributes of sensation from one sensory domain to another (Marks, 1975) has been attracting much attention (Köhler, 1992; Sathian, Ramachandran, 2019; Spence, 2015, 2019). Köhler (1992) using nonsense words he created “maluma” and “takete” asked people who were unaware of the purpose of the examination, showing two pictures one round shape and the other angular shape, which represents “maluma” or “takete”. He found almost all the people replied that the round shape was maluma and the angular shape is takete. Subsequently, two pictures round and jagged shape were shown to the people who were asked to reply which of two nonsense words “bouba” or “kiki” corresponds to the above two shapes. Almost all the people replied the bouba for round, and kiki for the jagged (Ramachamdran, Marcus and Chunharas, 2019).

The sound of eating a fruit or vegetable (celery, banana, strawberry, passion fruit, mango, apple, orange, and tomato）was chosen by three different groups, Spanish, German or French speaking subjects (Arboleda & Arce-Lopera, 2017). Eight texture terms (Crunch, Crack, Scratch, Chomp, Munch, Plup, Slurp, and Glub) were shown to subjects. These texture terms were categorized into strong (Crunch, Crack, Scratch), medium strong (Chomp, Munch) and soft (Plup. Slurp, Glup) although some differences were found among three language groups. Strong onomatopoeias were used for celery and apple, medium strong ones were used for banana, strawberry and mango, soft ones for passion fruit and orange, and for banana medium strong and soft words were used. The authors chose these eight texture terms from a dictionary of onomatopoeias. It was difficult to find a term “plup” in the internet, and it was not certain whether the subjects recognized the terms in the same way. In a subsequent study, the onomatopoeias, Ahhh, Glup, Fizzz were used to be corresponded to apple juices with different colors, red, green, yellow and control (Arroyo & Arboleda, 2021). These sound onmatopoeias were perceived before (Fizzz), during (Glup) and after (Ahhh) the consumption by 120 students at a Columbian university. As there was not so many papers reporting the sounds for liquid foods, this was a nice trial, but it was found that onomatopoeias were not universal. The corresponding onomatopoeia Fizzz in Japanese is *Shuwashuwa* or *zyuwa-zyuwa* representing the appearance of bubble ascending as seen for carbonated sparkling beverages (Hayakawa, Kazami, Nishinari, Ioku, Akuzawa, Yamano et al., 2013; Nishinari Hayakawa, Xia, Huang, Meullenet &Sieffermann, 2008; Sakamoto & Watanabe, 2016; Hanada, 2020).

Hanada (2020) collecting 771 texture terms from 50 subjects to whom 56 photos of different foods ‘celery, broccoli, asparagus, ,, grapes, apple, cherry, strawberry, ,,pizza, sausage ramen (Chinese noodle), white bread, rice cracker, pretzel, Baumkuchen, ,, cooked rice, ice cream,,,) were presented as stimuli. Since 359 words appeared only once, and thus eliminated. Retained 412 words were analyzed, and 15 dimensional configurations were plotted as asymmetrical biplot. Along the axis of dimension 1 were found noodles *udon* and ramen, and onomatopoeic words *zuruzuru, zuruQ*, where *Q* is used to represent the geminate clusters (double consonants), and gokugoku. These onomatopoeia *zuruzuru, zuru Q* were mimetic sounds and feelings when slurping noodles, which are thought to be not a good manner in European countries. Onomatopoeia *gokugoku* is used to represent the sensation and sounds of gulping liquids such as beer or juices. The dimension 1 is thought to represent texture related smoothness of noodles as well as mimetic sounds during slurping. Hanada continued such analysis for 15 dimensions. Although this new approach classified texture related onomatopoeia in an interesting way, it seems not perfectly logical. Some foods or texture words appeared more than once in different dimensions. Further development and clarification are expected to be done in the future.

A hierarchical cluster analysis based on the relationship between linguistic sounds and taste/texture evaluations revealed the structure of sensation categories. The results indicate that an emotional evaluation like pleasant/unpleasant is the primary cluster in gustation (Sakamoto & Watanabe,2016). The reason Japanese people use frequently onomatopoeic words in comparison with other nations remains a future problem (Nishinari et al., 2008).

* 1. **Significance of texture**

**2.3.1 Significance of texture**

Texture is a main factor together with taste and aroma to determine the palatability of foods (Szczesniak, 2002; Bourne, 2002; Nishinari, 2009).

The upper and lower limit of tolerance of a texture attribute is relatively wider than those for taste and aroma. However, when the texture deviates from the tolerance, consumers reject that food product. Crackers or biscuits are liked when they are crispy, but when they absorb some moisture, the crispness is lost, and they are not liked. When sand is not removed from shellfish or spinach, that will lead to unpleasant and unacceptable texture. Creamy texture of pudding, ice creams, and chocolate is also liked by most consumers while if these foods are not suitably cooked/produced, and show some gritty texture, they will not be liked. However, recently *nure-senbei*, wet rice cracker, which was made by soaking baked *senbei* (rice cracker) in soy sauce, was invented. Some consumers prefer wet rice crackers rather than traditional crispy/crunchy crackers, which are liked not only by tactile sensation but also by sound emission during biting.

Szczesniak (2020) says that the unexpected texture will not be acceptable, but there may be some surprising enjoyable texture which is unexpected and could make eating more attractive. There is no accounting for taste. The recent development of 3D printing technique has a potential to make a tailor-made food which is a favorite food for each individual not only by imitating or improving traditional favorite foods but also by creating a new palatable food incorporating multiple ingredients and controlling the shear stress and shear rate.

A recent meta-analysis recognized the influence of the texture on the satiety, appetite and food intake, but since pleasantness, palatability, acceptability, taste and favour also intervene, and it was difficult to be studied separately (Stribiţcaia, Evans, Gibbons, Blundell, & Sarkar, 2020). Stribiţcaia et al. (2020) found that solid food had stronger effect on the satiety, appetite and food intake than liquid food, viscous liquid stronger than less viscous. They also found that the longer time interval between the preload and the test meal made the texture effect less apparent, and stated more studies using a control condition, such as water or placebo condition, and clearly defined samples are necessary to see the effect of intervention (preload) excluding the effect of other factors pleasantness, palatability, acceptability, taste and favour.

**Impossible to distinguish different foods if the texture is the same**

Schiffman demonstrated indirectly the importance of texture examining whether humans identify correctly pureed and strained foods. She fed such 29 different foods with a similar consistency adding water when necessary to blindfolded subjects. Percentage of correct identification was examined for college students (18 females and 9 males) and elderly citizens (23 females and 6 males) (Schiffman, 1977) and for college students and obese patients (Schiffman, Musante, & Conger, 1978). Subjects were asked to smell a container of food presented at the level of nostrils, and then one spoonful to taste and to bring the food in contact with all parts of the mouth. Selected 29 foods were apple, banana, lemon, pear, pineapple, strawberry, walnut, acorn squash, broccoli, cabbage, carrot, celery, corn, cucumber, green bean, green pepper, potato, tomato, beef, fish, lamb, liver, pork, veal, cottage cheese, cream cheese, egg, coffee, rice, toasted-[wheat](https://en.wikipedia.org/wiki/Wheat) [cereal](https://en.wikipedia.org/wiki/Cereal), yeast, salt, and sugar. Sucrose (sweet), NaCl (salty), lemon (sour) and coffee (bitter) in a thin cornstarch matrix were used as four standards. The difference between males and females was not recognized. Bourne (2002) was surprised to notice that only 4% of the respondents could identify cabbage correctly by flavor only, 15% for pork, 41% for beef, and 51% for carrots. Schiffman, noticing that cucumber and cabbage were seldom recognized by both young and elderly, referred to the previous comments of Pangborn (1967) that nonflavor cues such as appearance, texture, and temperature are important in overall food recognition. It was also found that while young subjects recognize by both hedonic dimension (pleasant, good, refreshing, and fruity vs. obnoxious, repulsive, and nauseous) and ‘tactile’ dimension (sharp, bitey, pungent vs. weak, flat), tactile dimension was found lost in elderly subject. Flatness was found an unpleasant quality to the elderly.

Bourne points out that the large size of the dental industry in developed countries indicates the importance of the texture. It is possible to have a completely nutritious diet in the form of fluid foods, but people do not want to lose the gratifying sensation during mastication. He also cites the previous comments of Szczesniak that although texture is taken for granted and does not appear explicitly when it is within an acceptable range, it becomes a focal point of criticism and rejection of the food if it is not as it is expected to be (Bourne, 2002).

**Language labelling is helpful for distinction**

Texture terms in different languages will be discussed later. How the perception is influenced by language has been studied extensively, and language perception causality were demonstrated experimentally (Miller, Schmidt, Blankenburg, Pulvermuller, 2018). Miller et al (2018) presented four tactile stimuli each of which consists of 4 x 4 pins arranged in Braille-like to 9 female panellists who touched by the right middle finger. Among 16 pins of each stimuli, 4 pins were protruded, and subjected to longitudinal vibrations with different frequencies. In the concordant group of 4 stimuli, one stimulus was present 7 times more frequently than the other three stimuli. When two stimuli were presented to a panellist, she judges whether the second stimulus is the same to the first one or not (a two-alternative same-different forced choice judgement), and then she receives the feedback whether her judgement was right or wrong. The effect of verbal stimuli was examined using pseudoword which has no meaning and consisting of five sounds, consonant-consonant-vowel-consonant-consonant. Each tactile stimulus was accompanied by different verbal stimulus. Such training procedure continued for one week. The results showed that panellists could discriminate different stimuli better when it was accompanied with verbal stimuli concordantly than when it was accompanied discordantly (all the four tactile stimuli were accompanied with verbal stimuli with the same frequency).

**Texture plays a key role in safe eating**

Bourne (2002) pointed out reasons for masticating foods. 1) Gratification, 2) Comminution, 3) Mixing with saliva, 4) temperature adjustment, 5) Releasing flavor, 6) Increasing surface area.

Although the choking accident of konjac jelly was reported frequently several years ago by mass media, the most common suffocation leading to death was by *mochi,* sticky rice cake, especially on the New year’s day January 1(Kohyama, 2008). Development of newly designed food with new textures itself should not be discouraged, but it should be reminded that a new food sometimes encounter a new danger because consumers sometimes are not aware of the possible risk. Nobody will accuse the makers of a kettle when someone in their family suffers from a scald by boiling water because the danger of boiling water is well-known. Most common examples of choking are by *onigiri* (a rice ball) and *sushi* in Japan, but I have never heard that

someone accused the makers of these products even if they caused choking accidents*.* Silent aspiration is known to cause a pneumonia, and the study on the designing food to avoid the aspiration is now being performed as will be discussed later.

More information on food safety can be obtained from the website of Food Safety Commission of Japan <http://www.fsc.go.jp/english/index>.html. FSCJ publishes a specialized journal, Food Safety, which is an open access journal: www.jstage.jst.go.jp/browse/foodsafetyfscj. [Global Food Safety Curricula Initiative (GFSCI) | IUFoST](http://www.iufost.org/education/global-food-safety-curricula-initiative-gfsci-0)

Pneumonia caused by aspiration is an important case of death especially for elderly. It has been known empirically that high viscous liquid is safer than thin liquid such as water, tea, juice, consommé soup (thin and clear soup), and so some thickening agent is believed to be effective to prevent the aspiration. It was shown that the thickening is effective to lower the risk of aspiration. (Newman, Vilarde, Clavé, & Speyer, 2016). In addition to the viscosity, **Cohesiveness** has been attracting much attention recently in relation with the prevention of the aspiration. This will be discussed later in relation with Swallowing (Section 4.4).

The most important change in the texture during oral processing of solid foods is the gel-to- sol transition (Nishinari, 2021b). The cohesiveness of solid foods and that of liquid foods cannot be assessed by the same measurement method. The cohesiveness of semi-solid and particulated foods could be quantified by flowability factor originating from the powder technology (Tobin, Heunemann, Wemmer, Stokes, Nicholson, Windhab, & Fischer, 2017). The cohesiveness of liquid foods has recently been measured by extension test of the liquid filament (Hadde et al., 2019, Nishinari et al, 2019, Kongjaroen et al., 2022). The problem in the extension test is that the method cannot be applied directly to inhomogeneous substances, and to which extent inhomogeneity in the length scale can be applied is an urgent problem.

**2.3.2 Crispness**

Crispness is one of the most liked textural characteristics (Szczesniak, 2020), this has been studied by many food scientists (Kohyama, 2020). Szczesniak categorized crispy foods into two, dry/crisp (crackers, potato chips, bacon, toast etc) and wet/crisp (lettuce, celery, apple, radishes etc). In Unites States, many people like to eat crispy foods so much as described by (Szczesniak, 2000): “In the American culture, munching on crisp popcorn while watching a movie is a “must” for many consumers, often to the annoyance of other people in the theater”. Civille, Trail, Krogmann, and Thomas (2020) detailed the crispness of potato chips and bacons. But, this liked textural characteristics is not limited to USA, but also recognized in almost all the other countries, for example, for drian chips and broken rice-based crackers in Thailand (Pongsawatmanit, 2020), crispy bread called *Taftoon* or *Lavash* in Iran (Emadzadeh and Ghorani, 2020), fat bread called *Miassa* (produced both in *Valle D’Aosta* and *Piemonte* regions) and *Carasau* produced in Sardegna in Italy (DiMonaco, Miele, Puleo, Masi, and Cavella, 2020).

The crispness is an important attribute for a Japanese rice cracker, “*kakinotane*” (literally it means a seed (*tane*) of persimmon (*kaki*), because of the resemblance of the shape). Saita, Yamamoto, Raevskiy, Takei, Washio, Shioiri, & Sakai (2021) performed the sensory evaluation of the crispness sensation using common rice crackers, moisturized and then dried ones, and crushed versions. The 10 most frequently used words were selected and used as descriptors in the TDS (temporal dominance of sensations): *bari-bari, bori-bori, gari-gari, zaku-zaku* (for hard textures), *pari-pari, pori-pori, kari-kari* (for more crumbly textures), *saku-saku, sara-sara* (for light crispy textures), and *beta-beta* (wet and sticky texture). These onomatopoeic words have been used also in the Yoshikawa’s papers (1973a, 1973b and 1973c) in approximately the same meaning. By principal components analysis (PCA), the two principal components (PCs) with variance were found dominant. The variance of PC1, moisture characteristics (expressed by *beta-beta* and *saku-saku*), and PC2 hardness (expressed by *gari-gari* and *saku-saku*) contributed to 52% and 32%, respectively. These results suggested that the crispness of “*kakinotane*” should be evaluated using two scales.

The crispness of fresh fruits (e.g. apple) and vegetables (e.g. celery) or crispy dried foods such as biscuits, crackers, breakfast cereals, potato chips etc provide tactile, mechanical, acoustical enjoyment (Vickers, 1983; Civille, 2011). Here, the crispness is discussed briefly. Since Szczesniak noticed that the crispness/crunchiness is universally liked, Vickers (1983) expected that the sounds produced during eating contributes to our enjoyment and may themselves possess hedonic quality. Christensen and Vickers (1981) examined the relation between the crispness and the sounds using different products with varying crispness ranging from celery, turnip, crackers and biscuits. Biscuits and crackers were stored at different humidities, and the celery and turnip were blanched. They obtained the good correlation between the perceived crispness and the perceived loudness indicating that foods emitting louder sound were perceived crisper. However, intriguingly, they found this judgment of crispness was not affected by masking the sound with loud noise provided via headphone to subjects. They concluded that humans judge the crispness not only by sounds but it was also perceived by oral tactile sensations. Vickers (1983) found a good correlation between the pleasantness scores for the sounds produced by actual biting and chewing the same foods accompanied with the recorded sounds. A turnip was found to be an outlier because tactile (and other) cues were thought to be very important in addition to auditory cues.

Since pioneering works of Vickers (1983, 1984, 1985) on the acoustical attributes of texture, many efforts have been done to understand the role and the mechanism of sound emission and conduction. Although a crispy food was defined as “*a dry rigid food which, when bitten with the incisors, fractures quickly, easily, and totally while emitting a relatively loud, high-pitched sound”,* whereas a crunchy food is defined as “*a dense-textured food which, when chewed with the molars, undergoes a series of fractures while emitting relatively loud, low-pitched sounds”* (Vickers, 1984;Tunick et al., 2013), many authors did not distinguish the crispness from the crunchiness probably because most crispy foods are also crunchy. Tunick et al (2013) showed that crispness and crunchiness are highly correlated for dry crisp foods while the correlation between these two attributes were found not so highly correlated for wet crisp foods. The difference of the sound conduction in dried crispy foods and wet crispy foods, therefore, has been studied (Tunick et al., 2013). Crispness was also reviewed by many authors (Dias-Faceto, Salvador, Conti-Silva, 2019; Duizer, 2001; Vickers and Bourne, 1976a; Wang, Njehia, Katsuno, & Nishizu, 2020).

In the sensation of crispness of dried foods (crackers, biscuits, potato chips, breakfast cereals etc) and fresh fruits and vegetables (apple, celery, cucumber etc), auditory perception plays a primary role (Vickers and Bourne, 1976b; Tunick et al, 2013). Vickers noticed that the crispness of carrots and celery and evaluated by hand manipulation was almost twice less than that evaluated by biting, and attributed this lower scores of crispness obtained by handling to the marked flexibility of these vegetables. Vickers and Bourne (1976a) found that wet crisp products showed a much larger discrepancy between hand and bite judgments than did dry-crisp products. Their panellists found that the biting with the incisors was the best method of evaluation for the crispness of these foods.

Crispness is believed to be an important attribute for crispy foods, but most gel-like foods are not crispy, and textural characteristics of gel-like foods evaluated by mouth and hand are thought to be comparable as mentioned earlier.Many soft foods have been produced by food industry to help disadvantaged persons having a difficulty in mastication and swallowing. Some of these texture-modified foods are paste or puréed, and are not so appealing. Enzymatically softened meat, fish and vegetables have good looks and can give better appetite as mentioned earlier. This problem is discussed in the section on virtual reality approach.

**2.3.3 Creaminess**

As shown in **Table 2**, creaminess is an important attribute generally liked. Since the high intake of fat is an important cause of the obesity and cardiovascular diseases (Korakas et al., 2018), food industry tried to make reduced fat foods maintaining the palatability (Godoi, Ningtyas, Geoffroy & Prakash, 2021; Norton, Wallis, Spyropoulos, Lillford, & Norton, 2014). Although many studies have been done, the unanimous exact definition was not reached although some attributes like “smooth” and “thick” are commonly found in most papers (Upadhyay, Aktar & Chen, 2020). Dickinson (2018) pointed out a close connection between creaminess and perceived thickness, smoothness, mouth-coating and dairy flavor, and indeed, creaminess was found to correlate well with a higher viscosity (Akhtar, Stenzel, Murray, & Dickinson, 2005; Chojnicka-Paszun, de Jongh, & de Kruif, 2012). It was shown that droplet size reduction was effective to increase the creaminess and increased liking and also generated greater expectations of satiation and satiety (Lett, Norton, Yeomans, 2016). Another idea was to increase the viscosity to mimic the mouthfeel of dairy cream. Many polysaccharide thickening agents were used for this goal. Cellulose powders with submicron size were expected to make a cream-like texture (Hiraiwa, Ikeda, Takaya & Nishinari, 2002; Nishinari, Miyoshi, Takaya, 1998; Nsor-Atindana, Chen, Goff, Zhong, Sharif, & Li, 2017; Shi et al, 2014).

Recently, texture modification performance of microfibrillated cellulose (MFC) with a diameter of 3–4 nm, which is the size of elementary cellulose fibrils in primary cell walls originated from citrus fibres was examined and compared with that of xanthan (Blok, Bolhuis, Arnaudov, Velikov, & Stieger, 2021). It was reported that the length of individual MFC fibrils ca.10 μm (Hayden, Mohan, Imhof, & Velikov, 2019) and these fibrils form an attractive network. While xanthan solutions were found to show higher extensional viscosity at higher deformation rates, which was correlated with sensory perception of mouthcoating, slimy and sticky mouthfeel, which are generally disliked, MFC dispersions were found better in these aspects. However, a weak but not negligible cardboard flavour must be reduced and the dispersibility should also be further improved for the utilization in food industry (Blok et al., 2021). When MFC was used in low calorie mayonnaise, the undesirable cardboard flavour was not noticed probably because of stronger flavour of the product (Bolhuis, Arnaudov, Velikov, & Stieger, 2023), which is consistent with the findings of the other research group using nanocellulose fibres for low calorie mayonnaise substituting starch based thickeners (Heggset et al., 2020).

While the multi-faceted aspects of creaminess were emphasized to get a universal definition, the creaminess of a specific food is product dependent. For example, the creaminess for chocolate flavored milk was defined as “the perception of ‘oiliness’ in the mouth and the degree of a mouth-coating. Usually, creaminess is perceived only when a certain viscosity threshold is reached.” (Godoi et al., 2021). These authors found that the creaminess was higher for chocolate flavored milk prepared with collagen hydrolysate than gelatin although the thickness showed the opposite trend. This example shows that the definition of creaminess was not so well established.

W/O/W double emulsion are expected to be used for fat reduction while maintaining sensory perception of fat-related attributes such as creaminess because effective volume fraction of oil phase can be increased by manipulating the emulsification process. The incorporation of water droplets into w/o/w emulsions, where water droplets are emulsified and dispersed in the oil phase and thus the volume fraction of the oil phase increases or by clustering oil droplets, water is enclosed within the clusters, both of which increase the effective volume fraction of the dispersed phase (Oppermann, Verkaaik, Stieger & Scholten, 2017; Fuhrmann, Kalisvaart, Sala, Scholten, & Stieger, 2019; Fuhrmann, Sala, Stieger, & Scholten, 2020).

Emulsion gels consisting of emulsions of MCT and WPI mixed with gelling matrix of cold set acid-induced WPI, gelatin, κ-carrageenan, or mixture of κ-carrageenan and ι-carrageenan gels were examined to understand the creaminess perception (Sala, van de Velde, Cohen Stuart, van Aken, 2007). Oil droplet release was found to increase with increasing oil content in gelatin gels containing a Tween 20-stabilized emulsion, and the release was higher than in κ-carrageenan gels. The increase in the oil droplet release was attributed to the decrease in the modulus and the fracture stress of emulsion gels with increasing oil content because oil droplets were not bound to gel matrix. As was proposed by Dickinson and Chen (1999), the inactive (unbound) oil droplets were believed to decrease the mechanical strength of emulsion gels while the active (bound) oil droplets were thought to increase it. Sala et al. (2007) found that the oil droplet release was correlated with creamy and fatty attributes. Since these attributes were also found for gels containing bound oil droplets which showed a smaller amount of droplet release, these authors concluded that the droplet release was not the main mechanism affecting the creaminess perception. In a subsequent paper (Sala, de Wijk, van de Velde, & van Aken, 2008), the perceived creaminess was found increased with increasing emulsion concentration in gels of gelatin, κ-carrageenan, mixture of κ-carrageenan and ι-carrageenan than in WPI gels. Emulsion droplets were thought to be bound in WPI and gelatine gels, and were unbound in carrageenan gels based on the measurement of gel elastic modulus. The creaminess score was found higher in gels containing unbound oil droplets or melting in the mouth.

Lubrication behavior of emulsion-filled gels was thought to be another contributing factor to the creaminess based on friction coefficient measurement (de Wijk, & Prinz, 2005; Chojnicka, Visschers, & de Kruif, 2008). The creaminess score of homogenized milk, both creamy smell/taste and creamy mouthfeel, was found linearly increasing with decreasing friction coefficient (Chojnicka, de Jongh & de Kruif, 2012). Liu, Stieger, van der Linden & van de Velde (2015) studied the creaminess and fat-related perceptions for emulsion-filled gelatin gels where droplets were bound (using WPI as an emulsifier) or unbound (using Tween 20 as an emulsifier), and found that these perceptions were more strongly enhanced by unbound droplets than by bound droplets, that were caused by increased coalescence and a lower friction. Less coalescence was observed for bound droplets than for unbound droplets by CLSM. They also found more coalescence and low friction in emulsion-filled gels containing droplets with higher SFC (solid fat content) than with lower SFC (SFC was determined at 20 ºC by pulsed NMR). Although they found that emulsion gels with higher SFC showed more coalescence and lower friction, they also found that SFC did not influence fat-related perception. In emulsions, showing more coalescence and lower friction led to the higher fat-related perception (Dresselhuis, Klok, Stuart, Vrie, van Aken & Hoog, 2007), but this was not the case in emulsion-filled gels. This was attributed to the complicated breakdown behavior in gels than in emulsions (Liu et al.,2015).

Effects of droplet clustering was studied for O/W emulsions with different sets of emulsifiers: (a) positively charged gelatin and negatively-charged whey protein (WPI), and (b) positively-charged gelatin and negatively-charged diacetyl tartaric acid ester of mono- and diglycerides (DATEM) (Fuhrmann et al., 2019). Sensory properties were found to be dependent on the strength of clusters. The interaction strength of clustered emulsions was estimated by the critical strain in the strain sweep of the storage modulus *G*ʹ from 0.01% to 100% at 20 ºC at a fixed angular frequency of 10 rad s-1. Critical strain was defined as the strain at which *G*ʹ deviated by 5% from the values found in the linear viscoelastic regime. The critical strain was around 2% for GW55 (gelatin and WPI (50%/50%)) and 4% for GD55 (gelatin and DATEM (50%/50%)). Thus, the stronger electrostatic attraction within clusters stabilized with gelatin and DATEM (GD) led to a 2× higher critical strain compared to clusters with gelatin and WPI (GW) due to differences in charge density of the emulsifiers. Emulsions with weakly bound clusters (GW) were perceived as creamy, whereas emulsions with strongly bound clusters (GD) were perceived as grainy, even though cluster size was similar. For strongly bound clustered o/w emulsions (GD), graininess increased with increasing cluster size. This increase in graininess intensity was not observed for weakly bound clustered o/w emulsions (GW). Although the interaction between gelatin and DATEM was found strong while that between gelatin and WPI was weak, this was unfortunately indicated oppositely in Fig.1 of Fuhrmann et al. (2019), which was now confirmed by the corresponding author.

In the subsequent study using the above mentioned sets of emulsifiers, the effects of length scales on the rheological and sensory properties of emulsion-filled gels were studied by (1) clustering of o/w-emulsions by hetero-aggregation and subsequent gelation to obtain inhomogeneity at μm-scale, and (2) incorporating particles of emulsion-filled gels into emulsion-filled gel matrices with a different volume fraction of oil droplets to obtain gel-in-gels with inhomogeneity at mm-scale (Fuhrmann, Sala, Stieger & Scholten, 2020). Three single droplet O/W emulsion, WPI-stabilized emulsion, gelatin-stabilized emulsion, DATEM-stabilized emulsion and two kinds of hetero-aggregated O/W emulsions by combining (a) DATEM- and gelatin-stabilized O/W emulsions (pH 5), and (b) WPI- and gelatin-stabilized emulsions (pH 7) were prepared.

In the examination of the effects of droplet clustering at μm-scale, the creaminess perception was found highest for GD01 (DATEM-stabilized droplet, size 2.0 μm). This sample showed the weakest mechanical properties, Young’s modulus *E* = 58 kPa, fracture stress *σ*f = 11kPa, fracture strain *ε*f = 0.2, while GD10 (gelatin-stabilized droplet, size 2.5 μm) had *E* = 86 kPa, fracture stress *σ*f = 33kPa, fracture strain *ε*f = 0.38. This was attributed to the experimental findings that the DATEM-stabilized droplets are unbound to the gellan matrix while gelatin-stabilized droplets are bound (Fuhrmann et al., 2020). General rules which govern whether oil release was enhanced in unbound droplets than in bound droplet, or the interaction between droplets and the matrix can be determined by electrostatic interaction etc were found difficult to establish because of so many factors: the fracture strain of the droplets cannot be predicted only from the difference in bound or unbound because synergistic interaction between gelatin and gellan also intervene this problem. While emulsion-filled gelatin gels with unbound emulsion droplets showing lower fracture strain, that is brittle, were found creamier which is in line with the previous findings (Liu et al., 2015; Sarkar et al., 2017), the opposite phenomenon that emulsion-filled gels with higher fracture strain were perceived creamier was reported (Devezeaux de Lavergne, Strijbosch, van den Broek, van de Velde, & Stieger, 2016).

In the examination of the effects of droplet clustering at mm-scale, three kinds of homogeneous gelatin gels containing 5, 17.5 and 30% sunflower oil, and three kinds of “gel-in-gel” containing 17.5% oil samples consisting of gelatin particles in gelatin matrix (Fuhrmann et al., 2020). Gelatin particles containing WPI-stabilized O/W emulsions with 5, 17.5 and 30% sunflower oil were mixed with gelatin matrix containing 30, 17.5 and 5% sunflower oil in the volume ratio 1:1, respectively, so that the oil content of all the “gel-in-gel” samples is 17.5%. In homogeneous gelatin gels, both *E* and *σ*f increased and *ε*f decreased with increasing oil concentration from 5% → 17.5% → 30 %, which was attributed to the bound filler nature of the WPI-stabilized oil droplet in gelatin matrix. Gelatin used has a slight positive charge at pH 7 while WPI stabilizing oil had a negative charge, and thus the attractive electrostatic interaction occurred between emulsion droplets and the matrix. All the mechanical parameters for *E* and *σ*f increased and *ε*f decreased s *E*, *σ*f, and *ε*f showed similar values and smaller than those for homogeneous gelatin gels. The oil flavor and oiliness perception were lowest in the“gel-in-gel” sample with the lowest oil content (5%) in the continuous phase than in those with higher oil content (17.5% and 30%). This observation interpreted as follows: more oil droplets could reach oral surfaces, and thus higher oil concentration led to higher oiliness and oil flavour. But, the creaminess perception did not show the same tendency; the“gel-in-gel” sample with the highest oil content (30%) in the continuous phase showed the lowest creaminess. This finding is contradictory with the previous finding by Mosca et al (2012) who reported that the creaminess tended to increase with increasing inhomogeneity of the oil droplet distribution. Fuhrmann et al. (2020) did not observe an increase in creaminess with an inhomogeneous distribution. In addition, the gel-in-gels containing the lowest oil concentration in the continuous phase were perceived as more mouth coating and more lingering. Therefore, the authors thought that oil related perceptions could not be determined by oil release solely, and it was necessary to take into account the melting behavior.

Microgels or fluid gels were found effective to reduce the friction coefficient, and to produce cream-like texture (Fernandez-Farrés, 2015; Fernandez-Farrés & Norton, 2015; Garrec, 2013; Garrec & Norton, 2012). Since creaminess perception is a multi-faceted sensation, it could be perceived by visual, olfactory, gustatory, and tactile sensation (Upadhyay et al., 2020).

Tactile sensation was thought to be dominant for creaminess, and thus was related with the smoothness opposite to the grittiness, therefore could be realized by decreasing the particle size in foods. Examination of sensory perception of protein microparticles, Singer and Dunn (1990) found that suspensions with particle size below 0.1 μm gave viscous watery sensation, those between 0.1 and 3 μm were creamy and those above 3 μm were felt gritty (Singer and Dunn, 1990). The minimum particle size that can be detected by the palate was reported as 25 μm by the confectionery literature (Engelen et al., 2005). More recently, it was suggested that naive chocolate consumers (i.e., non-experts) were able to perceive differences in chocolate particle size when they differ by only ~5 micrometers (microns) (Breen, Etter, Ziegler, & Hayes, 2019).

It is well known that grittiness or smoothness depend not only the particle size but also on hardness, volume fraction, particle shape; round and soft particles present in mayonnaise or yogurt are not perceived gritty while anisotropic shaped particles with hard edges are perceived as gritty (Engelen et al., 2005). This will be discussed later again.

Humans do not perceive the creaminess for suspensions of nanoparticles of plant origin not because of the size but by the lack of milk flavor. The perception of creamy sensation may be limited to dairy products, and thus the definition of creaminess should be clarified. The creaminess is not equivalent to the smoothness. Although the fluid gels or similar microparticulated gels could well mimic the tribological properties of dairy cream from milk, humans don’t feel the creamy sensation which has been always coexisting with milk flavor.

MCC is insoluble and can mimic fat texture and sensory perception, it can fill the void without affecting the other ingredients, and thus is used in cocoa beverages, low-fat sauces, dressings, and beef patties giving the creamy texture (Nsor-Atindana et al., 2017). Various kind of polysaccharides by virtue of its function lubrication, fat replacement, and WHC have been used in the fabrication of low-fat foods (Yang, Li, Li, Sun, Guo, 2020).

The role of saliva in the creaminess perception should be more clarified (Upadhyay et al., 2020). It was also found that there was no significant difference in the friction coefficient *μ* between the bound and unbound emulsion-gels, although *μ* of both types of emulsion-gels decreased with increase of oil concentration. The fragmentation and structure failure of the emulsion-gels under shear were believed to weaken the difference (Yang, Feng, Su, Wang, Zhang, Wei, et al., 2020).

**2.3.4 Juiciness**

Juiciness is one of the most liked texture attributes as listed in Table 1. Juiciness plays a key role in meat, vegetables and fruits. Juiciness is an important attribute determining the palatability of fruits and vegetables along with firmness, flavor, good balance of sweet and sour. Both firmness and juiciness are determined by the strength of cell walls, the cohesiveness of the [middle lamella](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/middle-lamella) and the cell [turgor](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/turgor). Important cell wall components of fruits are hemicellulose and pectins, and the latter is solubilized, depolymerized and its neutral side chains are eliminated during fruit ripening leading to the softening (Mercado, Matas, & Posé, 2019). Juiciness wets and refreshes the mouth and its absence violates expectations and lowers the perceived quality. Juiciness in fruits and vegetables are implemented by high water content, organized cellular network with proper turgor and integrity, cell walls mechanically weaker than the middle lamella (so that on biting the break in the tissue occurs across and not in between the cell walls), low viscosity, and little suspended solids in the expressed liquid. Juiciness increases with increasing cell size and decreasing cell wall thickness (Szczesniak, 2020).

In contrast to food products of plant origin in which the juice is composed primarily of water, juiciness in meats is derived from a mixture of expressible water and liquid fat. Juiciness is one of the key factors determining the palatability of meat along with tenderness and flavor. It is influenced by the characteristics of raw meat and the manner of cooking. Greater marbling (i.e. the visual representation of intramuscular fat) in raw meat and searing (i.e. application of intense heat to the surfaces of raw meat) as the first step in cooking will increase juiciness. Searing forms a crust difficult for water to penetrate, thus “sealing in the juices” (Szczesniak, 2020).

When beef is heated, cooking loss increases and the juiciness decreases with increasing temperature. It was reported that juiciness score by trained panel after 3 or 10 chews was linearly related with intramuscular fat (IMF%) content of beef longissimus (Warner, 2017). Recently, consumer palatability or eating quality of beef was found in close correlation with IMF % based on a large scale observation (Stewart, Gardner, McGilchrist, Pethick, Polkinghorne, Thompson, & Tarr, 2021).

The juiciness decrease accompanying cooking loss was explained by protein denaturation, and was analyzed by modified Flory-Rehner model for polyelectrolytes gels. WHC was expressed as the swelling ratio which is the inverse of the volume fraction. The validity of such analysis was demonstrated by the agreement of water distribution in roasted beef which showed a sigmoidal decrease with increasing temperature (van der Sman, 2007). This approach was found applicable also for mushrooms (Paudel, Boom, van der Sman, 2015).

Juiciness sensation may occur when inner liquid water or liquid fat exudes out on chewing, and therefore it is closely related with water/liquid fat holding capacity. Microcrystalline cellulose (MCC) forms a particle gel network as an inert molecule because it is insoluble and fills the gaps of the tight meat fiber network without causing any disturbance to the protein network during heating. In emulsified sausage, MCC enhances the firmness of the final product due to its high compatibility in the meat matrix (Gibis, Schuh, &Weiss, 2015; Zhang, Zhang, & Yuan, 2021). Bacterial cellulose is also used in meat and sea food products by virtue of its high WHC (Shi, Zhang, Phillips, & Yang, 2014).

Juiciness, water holding capacity (WHC) as well as tenderness of meat products were found to be improved by applying interpenetrating network hydrogels by virtue of their denser cross-linked networks than single network gels (Du, Lu, Zhang, Mata, Fang, 2021).

Although the incorporation of *okara* containing 40-65 dietary fiber into tofu worsen the WHC and smoothness, the particle size reduction used in nanocellulose technologies (Nagano, Hirano, Kurihara, & Nishinari, 2020) or layer-by-layer coating of *okara* particles by chitin/pectin (Wei, Ye, Li, Wang, Li, & Zhao, 2018) achieved successfully the goal to increase the dietary fiber content without damaging the smooth texture of tofu. The performance of layer-by-layer coating of *okara* particles by chitin/pectin to keep the tofu shape against the mechanical vibration was attributed to the interaction between the pectin layer of coated particles and the proteins in the continuous phase of tofu, previously reported for soy protein and sugar beet pectin interpenetrating network (Hou, Guo, Wang, He, Yuan, Yin, et al., 2015).

Water distribution in plant protein mixture has been studied by time domain NMR (TD -NMR) and rheological model for composite materials, iso-strain, iso-stress and bi-continuous (Dekkers, Kort, Grabowska, Tian, As, & van der Goot, 2016). WHC determined by centrifugation method was previously reported from the same laboratory as 8.9 g water/g dry matter and 1.9 g water/g dry matter for soy protein isolate (SPI) and wheat gluten (WG), respectively. In mixed systems of SPI and WG with different mixing ratios (80/20, 65/35, 50/50, 35/65, 20/80) and concentrations (0.25, 0.30, 0.35, 0.40 wt%), volume fraction determined by TD-NMR and rheology was found higher for SPI than for WG in untreated protein dispersions, protein gels or fibrous samples prepared in the high temperature shear cells (Dekkers et al., 2018). This was thought to indicate that the water distribution was not influenced by the heat and shear processing, and that more water was absorbed by the SPI phase compared with WG phase. However, which blending law model of iso-strain, iso-stress and bi-continuous models gives the best fit could not be determined. Since both SPI and WG are poly-ampholytes, the swelling ratio could be controlled by changing pH and ionic strength. At low and high ionic strengths, the swelling was reduced, and at intermediate ionic strengths, swelling and thus the juiciness might be increased by lowering ionic strength of bath (marinade) (Cornet, Snel, Lesschen, van der Goot, & van der Sman, 2021). Since the swelling can be controlled also by the cross-link density, Cornet et al (2021) showed that with increasing glutaraldehyde (GA) and dithiothreitol (DTT) the swelling ratio was decreased. Since GA and DTT are not suitable in food application, they suggested to use transglutaminase and papain should be used in the following experiment.

1. **Texture sensation**

**3.1 Physiological bases of sensation**

Before the ingestion of food or beverages, humans judge the edibility by seeing, hearing, smelling, and touching. During mastication and swallowing, tasting (gustation) and smelling (olfaction) play dominant roles but hearing (auditory) sensation becomes dominant for crisp or crunchy foods. All these sensations interact with foods and the perception is a result of the interaction of all these sensations transmitted to the central nervous system (CNS) (Betts, Desaix, Johnson, Johnson, Korol, Kruse et al., 2017; Elbert, Kroemer, Hoffman, 2018; Sathian, Ramachandran, 2019).

The classification of human senses into five, vision, audition, olfaction, gustation and taction has been used since Aristotle, although other sensory abilities such as the kinesthetic sense (*proprioception*), the sense of balance (*equilibrioception*), and the ability to detect salt and carbon-dioxide concentrations (*chemoreception*) were not included. In addition, taction is now thought to include more than one sense, because one feels several mechanical stimuli, such as contact and pressure, often together with pain (*nociception*), electricity (*electroreception*), and temper­ature (*thermoception*).

The group of sensory modalities that are associated with touch, proprioception, and interoception is called somatosensation. These modalities include pressure, vibration, light touch, tickle, itch, temperature, pain, proprioception, and kinesthesia. This means that its receptors are not associated with a specialized organ, but are instead spread throughout the body in a variety of organs. Many of the somatosensory receptors are located in the skin, but receptors are also found in muscles, tendons, joint capsules, ligaments, and in the walls of visceral organs (Betts, et al, 2017).

At the level of the oral cavity, oral functions are regulated and coordinated by a sensorimotor control involving many sensory inputs from oral receptors relaying information on what happens in the mouth.

Major oral structures involved in mastication and swallowing are the teeth, jaws, tongue, masticatory muscles, which are helped by saliva. The masticatory system is constituted of two jaws supporting teeth, namely the maxillary jaw which is part of the skull and the mandibular jaw also named the mandible whose displacements are guided by the temporo-mandibular joints. Sensory inputs from these elements are conveyed by the fifth cranial nerve toward a group of neurons named the central pattern generator (CPG) in the brainstem (Lund, 1991).

**3.1.1 Sensory Receptors**

Different types of stimuli are sensed by different types of receptor cells in the peripheral nervous system. Receptor cells can be classified into types on the basis of three different criteria: 1) structural receptor type, 2) location relative to stimuli, and 3) functional receptor type or how the receptor transduces stimuli into membrane potential changes.

1) structural receptor type; A neuron that has a free nerve ending, with dendrites embedded in tissue that would receive a sensation locating on the dermis of skin, stimulated by pain and temperature. A neuron that has an encapsulated endingin which the sensory nerve endings are encapsulated in connective tissue that enhances their sensitivity stimulated by pressure and touch. A specialized receptor cell, which has distinct structural components that interpret a specific type of stimulus, e.g. a photoreceptor (Betts et al, 2017).

2) location relative to stimuli; An exteroceptoris a receptor that is located near a stimulus in the external environment, such as the somatosensory receptors that are located in the skin. An interoceptoris one that interprets stimuli from internal organs and tissues, such as the receptors that sense the increase in blood pressure in the aorta (the largest artery in the body) or carotid sinus (dilated area of the carotid artery). Finally, a proprioceptoris a receptor located near a moving part of the body, such as a muscle, that interprets the positions of the tissues as they move.

3) functional receptor type; Stimuli are of three general types. Some stimuli are ions and macromolecules that affect transmembrane receptor proteins when these chemicals diffuse across the cell membrane. Some stimuli are physical variations in the environment that affect receptor cell membrane potentials. Other stimuli include the electromagnetic radiation from visible light. For humans, the only electromagnetic energy that is perceived by our eyes is visible light. Some other organisms have receptors that humans lack, such as the heat sensors of snakes, the ultraviolet light sensors of bees, or magnetic receptors in migratory birds.

Receptor cells can be further categorized on the basis of the type of stimuli they transduce. Chemical stimuli can be interpreted by a **chemoreceptor** that interprets chemical stimuli, such as an object’s taste or smell. **Osmoreceptors** respond to solute concentrations of body fluids. Additionally, pain is primarily a chemical sense that interprets the presence of chemicals from tissue damage, or similar intense stimuli, through a **nociceptor**. Physical stimuli, such as pressure and vibration, as well as the sensation of sound and body position (balance), are interpreted through a **mechanoreceptor**. Another physical stimulus that has its own type of receptor is temperature, which is sensed through a **thermoreceptor** that is either sensitive to temperatures above (heat) or below (cold) normal body temperature.

Table 3 Mechanoreceptors of Somatosensation. \*No corresponding eponymous name (Betts et al., 2017, p629/1420, Table 14.1).

**Figure 3** A cross section of glabrous (without hairs or projections) skin, showing the layers of the skin and the structure, firing properties, and perceptions associated with the Merkel receptor and Meissner corpuscle—two mechanoreceptors that are near the surface of the skin. Goldstein (2010, Figure 14.1)

**Figure 4** A cross section of glabrous skin, showing the structure, firing properties, and perceptions associated with the Ruffini cylinder and the Pacinian corpuscle—two mechanoreceptors that are deeper in the skin (Goldstein 2010, Figure 14.2).

Merkel cells are located in the stratum basale of the epidermis, and sense low frequency vibration such as ones when a finger drags across a textured surface. Pacinian corpuscles are located deep in the dermis or subcutaneous tissues and transduce deep pressure and vibration.

Meissner corpuscles respond to the light touch. Ruffini corpuscles are located in the cutaneous tissue between the dermal papillae and the hypodermis, and transduce the stretching of the skin.

Temperature receptors are stimulated when local temperatures differ from body temperature. Some thermoreceptors are sensitive to just cold and others to just heat. Capsaicin, a main component of red pepper, was found to bind to a transmembrane ion channel in nociceptors (receptor cells that sense potentially damaging or pain stimuli) that is sensitive to temperatures above 37°C, and this capsaicin receptor is named TRPV1. Menthol, a main component of peppermint, was found to stimulate TRPM8, cold-and menthol-sensitive receptor 1 (CMR 1). These discoveries stimulated further research to understand the perception of temperature and pain, and were awarded Nobel Prize in 2021.

Human sensory sensor consists of the receptor which receives proximal stimulus, and the converter which transforms the received stimulus to electric potential, and sends to central nervous system (CNS) through neuron. Many stimuli are filtered out if they are not strong, and

humans adapt to harmless stimuli, for example, the adaptation of taction to the feeling of clothes worn. The nervous discharge is reduced when the second stimulus appears as in the situation where the vigorous rubbing of a stubbed toe. This inhibition of the signal rejection masks the pain that was originally felt (Elbert, Kroemer, Hoffman, 2018).

The *difference threshold* is the smallest phys­ical difference in the amount of stimulation that produces a just noticeable difference (JND) in the intensity of our sensation. This threshold was investigated by Gustav Fechner and Ernst Weber in the 19th century. Table 4 shows the smallest energies that are detectable and the largest energies that are tolerable or practical. Stimuli near either of these limits could not be sensed correctly (Elbert, Kroemer, & Hoffman, 2018).

Table 4 Characteristics of human senses (Elbert, Kroemer, & Hoffman, 2018)

**Digestive function of the mouth**

When foods are ingested, oral organs work harmoniously to masticate, shredding, crushing, mixing with saliva, forming bolus and send to esophagus.

Table 5 Digestive Functions of the Mouth (Betts et al., 2017)

**3.1.2 Teeth**

Between approximately age 6 and 12, twenty baby teeth (deciduous teeth) are replaced by 32 permanent teeth. From the center of the mouth toward the side, 8 incisors (four top and four bottom), then 4 cuspids (or canines), then posterior to the cuspids are 8 premolars (or bicuspids), and then 12 molars at the most posterior site. The incisors are used for cutting food, the canines for tearing, the premolars for grasping, and the molars for grinding (masticating). (Healy, 2016).

The teeth are secured in the sockets (alveolar processes) of the maxilla and the mandible. Teeth are also held in their sockets by a connective tissue called the **periodontal ligament**.

The upper part of a tooth is called crown which is projecting above the **gingivae** (called a gum), and the lower part is the root which is embedded within the maxilla and mandible. Both parts contain an inner **pulp cavity**, containing loose connective tissue through which run nerves and blood vessels. The region of the pulp cavity that runs through the root of the tooth is called

the root canal. Surrounding the pulp cavity is **dentin**, a bone-like tissue. In the root of each tooth, the dentin is covered by an even harder bone-like layer called **cementum**. In the crown of each tooth, the dentin is covered by an outer layer of **enamel**, the hardest substance in the body **(**Figure 5**)** (Betts et al, 2017).

Figure 5 The Structure of the Tooth. This longitudinal section through a molar in its alveolar socket shows the relationships between enamel, dentin, and pulp (Betts et al., 2017, Figure 23.11).

The enamel was considered harder than dentin, and thus enamel has higher wear resistance, making it suitable for grinding and crushing foods, and dentin has higher force resistance, making it suitable for absorbing bite force (Chun, Choi & Lee, 2014). Chun et al. (2014) and Healy (2016) reported the mechanical properties of enamel and dentin. The elastic modulus of enamel is ca 80 GPa and that of dentin ranges from10 to 20 GPa, but the data depend on the number of collected samples (Brauer, Saeki, Hilton, Marshall, & Marshall, 2008).

**3.1.3 Muscle activity**

Numerous skeletal muscles are involved in mastication. Their contraction generates mandibular movements and forces adjusted to food and food bolus resistance.

Muscles involved in chewing must be able to exert enough pressure to bite through and then chew food before it is swallowed (Fig. 5 and Table 4). The **masseter** muscle is the main muscle used for chewing because it elevates the mandible (lower jaw) to close the mouth, and it is assisted by the **temporalis** muscle, which retracts the mandible. We can feel the temporalis move by putting our fingers to our temple as we chew.

Although the masseter and temporalis are responsible for elevating and closing the jaw to break food into digestible pieces, the **medial pterygoid** and **lateral pterygoid** muscles provide assistance in chewing and moving food within the mouth.

Fig. 6 Muscles That Move the Lower Jaw. The muscles that move the lower jaw are typically located within the cheek and originate from processes in the skull. This provides the jaw muscles with the large amount of leverage needed for chewing (Anatomy and Physiology, Betts et al, 2017, Figure 11.10).

Table 6 Muscles of the Lower Jaw (Betts et al, 2017)

**Muscles That Move the Tongue (Betts, 2017)**

Although the tongue is obviously important for tasting food, it is also necessary for mastication, **deglutition** (swallowing), and speech (**Fig.6, Table 6**). Because it is so moveable, the tongue facilitates complex speech patterns and sounds.

Figure 7 Muscles that Move the Tongue (Betts et al, 2017, Figure 11.11)

Table 7 Muscles for Tongue Movement, Swallowing, and Speech (Betts et al, 2017)

The extrinsic muscles (inserting into the tongue from outside origins) move the whole tongue in different directions, whereas the intrinsic muscles (inserting into the tongue from origins within it) allow the tongue to change its shape (such as, curling the tongue in a loop

or flattening it). Names of the extrinsic muscles all include the word root glossus (glossus = “tongue”), and the muscle names are derived from where the muscle originates. The **genioglossus** (genio = “chin”) originates on the mandible and allows the tongue to move downward and forward. The **styloglossus** originates on the styloid bone, and allows upward and backward motion. The **palatoglossus** originates on the soft palate to elevate the back of the tongue, and the **hyoglossus** originates on the hyoid bone to move the tongue downward and flatten it (Betts et al., 2017).

A clear relationship between food hardness and jaw muscle activity has been reported in numerous studies. Increased jaw muscle activity and longer duration of the muscle activity were observed for harder foods (Agrawal & Lucas, 2002; Foster *et al*., 2006; Horio & Kawamura, 1989 ; Mioche *et al* ., 1999 ; Peyron *et al* ., 2002 ; Plesh *et al*., 1986 ; van der Bilt, 2012; van der Bilt *&* Abbink, 2017 ). It was shown that the hardness of chewing gum (soft or hard gum) influenced the chewing cycle duration and the amplitude of the muscle activity. The subjects chewed slower and with more muscle activity on the hard gum (Plesh *et al*., 1986). This will be discussed later.

In another study muscle activity was measured while subjects chewed on 15 different types of food (various kinds of cheeses, nuts and carrots), which largely varied in mechanical properties (Agrawal *et al*., 1997, 1998). Young’s modulus and toughness were measured for each food. Young’s modulus (or elastic modulus) was determined from the slope of a force -deformation curve of the material. Toughness is the resistance to fracture of a material when stressed and was measured by a wedge test. Muscle activity needed to chew the various food types turned out to be significantly related to the square root of the ratio of toughness and the modulus of elasticity (p < 0.0001). The influence of food characteristics on chewing was also studied using model foods (Foster *et al*., 2006).

Kohyama et al. (2015) examined the eating difficulty by EMG for five model food gels with different textures. EMG variables of jaw closing muscles (right and left masseter muscles) and jaw-opening and tongue movement muscles (suprahyoid muscles) were measured since the eating difficulty comprises several factors such as difficulty in deforming, cutting off, crushing, moving, gathering chewed fragments, flowing, difficulty in chewing, forming a bolus, and swallowing (Hayakawa et al., 2014). Hayakawa et al. (2014) evaluated the eating difficulty using a panel consisting of 12 trained subjects (11 females and one male, age 32–54 years old). Kohyama et al. (2015) using EMG found that the time for oral processing was longest (20.1s) for the most difficult sample, a gel consisting of 1% kappa-carrageenan + 1% locust bean gum, and the shortest (6.6s) for the easiest sample a 3% gelatin gel. Although gelatin did not completely melt at body temperature, partial melting may occur, but it may not be the most important factor which makes gelatin the easiest. Kohyama et al. (2015) also found that total duration and activity of masseter and suprahyoid were also largest for the most difficult gel and smallest for the easiest gel. Thus, they clearly showed that the eating difficulty of these five gels were quantified by EMG variables. Kohyama et al. (2017), using three gellan gels with a similar fracture load but different fracture strains and three gellan gels with a similar fracture strain at the middle level but three different fracture loads, tried to find the best parameter to characterize the transition from the tongue-palate compression to teeth chewing. Since the sensory evaluation sometimes gave ambiguous judgment of panelists on these two strategies for size reduction, they compared the EMG data with mechanical properties of gellan gels. The deformation profile during the uniaxial compression of a gel set on the glass stage was determined by a video camera, and the true fracture stress was determined. Kohyama et al. (2017) found that the true fracture stress correlated well with EMG and thus with the selection of the strategy in oral processing.

**3.1.4 The tongue**

The tonguefunctions in positioning the ingested food confining in the mouth to prevent going out from the oral cavity cooperating with lips and cheeks and positioning it between teeth, and the formation of bolus during chewing and then transport to the posterior part of oral cavity. It works also as a mechanical tool to crush soft foods, as a chemical digestion (lingual lipase), and

sensation of taste, texture, and temperature of food, swallowing, and vocalization (Betts, Desaix, Johnson, Johnson, Korol, Kruse et al., 2017).

The muscle mylohyoid raises the tongue, the muscle hyoglossus pulls it down and back, the muscle styloglossus pulls it up and back, and the muscle genioglossus pulls it forward. Working in concert, these muscles perform three important digestive functions in the mouth: (1) position food for optimal chewing, (2) gather food into a bolus, and (3) position food so it can be swallowed (Betts et al, 2017). On the surface of the tongue, there are raised bumps called papillae which contain the structures for gustatory transduction. The papillae are classified into four types based on their appearance: circumvallate, foliate, filiform, and fungiform. Within the structure of the papillae are taste budsthat contain specialized gustatory receptor cellsfor the transduction of taste stimuli, which is discussed in the accompanying paper.Fungiform papillae, which are mushroom shaped, cover a large area of thetongue; they tend to be larger toward the rear of the tongue and smaller on the tip and sides. In contrast, filiform papillaeare long and thin. Fungiform papillae contain taste buds, and filiform papillae have touch receptors that help the tonguemove food around in the mouth. The filiform papillae create an abrasive surface that performs mechanically, much like acat’s rough tongue that is used for grooming (Betts et al, 2017).

Figure 8 The superior view of the tongue showing the locations and types of

lingual papillae (Betts et al, 2017, Figure 23.8)

Humans chew hard foods with teeth, but use the tongue for crushing soft foods. In such a situation, the elastic modulus of the tongue is an important parameter. The apparent Young’s modulus *E* of the human tongue was measured by inserting the tongue between the probes of the digimatic micrometer at 20 ± 5.1% strain. Observed values of *E* were 1.22 ± 0.42 × 104 Pa in a relaxed state and 12.25 ± 5.85× 104 Pa in a tension state (Ishihara, Nakao, Nakauma, Funami, Hori, Ono, et al., 2013).

The role of the tongue in the transport and propulsion from the anterior to posterior oral cavity was studied in vitro and simulation by Marconati, Engman, Burbidge, Mathieu, Souchon & Ramaioli (2019) focusing on the squeezing of the tongue against the palate, tongue-induced peristaltic motion in oropharyngeal cavity, and bolus containment and propulsion.

Noel and Hu (2018) examined the gripping function of the tongue. In the food oral processing the ingested food should not be propelled to the pharynx before it is processed into a bolus, crushed down into small fragments and mixed with saliva, and forming a cohesive bolus. Noel et al. (2018) pointed out that saliva as a shear thinning fluid helps the tongue to function well as a gripper.

**Since the soft gel-like foods are compresses/squeezed between the tongue and the palate, the tongue pressure recording gives the clue for understanding the swallowing. The tongue pressure detected at 5 points in the oral cavity (Ch1, anterior; Ch2 and Ch3, midcentral; Ch4 and Ch5, lateral posterior) showed peaks four times during squeezing (Figure 7).**

Figure 9 Tongue pressure waveforms recorded during the ingestion of 10 mL of hard jelly made of high acyl gellan and psyllium seed gum. Each stage of squeezing and swallowing was identified by the synchronous recording of videoendoscopic imaging; a, start of pharyngeal propulsion; b, arrival of the jelly at epiglottic vallecula; c, onset of whiteout; d, end of whiteout. (Hayashi et al., 2013; Nishinari et al, 2020).

From the first to the third peak, the tongue pressure was higher at anterior parts and showed the highest value at the 3rd squeezing. At the last stage just before swallowing (the 4th peak), the lateral posterior pressure detected by Ch4 and Ch5 was higher than the anterior (Ch1) and the mid central (Ch2 and Ch3). The tongue pressure reached maximum just before swallowing.

A similar tendency was reported based on a similar measurement of the tongue pressure (Kieser, Farland, Jack, Farella, Wang, & Rohrle, 2014).

**3.1.5 Saliva**

During the bolus formation in oral processing, food is broken down into small fragments and mixed with saliva. Saliva plays an important role to make a cohesive and lubricated bolus for safe swallowing (Boehm, Yakubov, Stokes & Baier, 2020; Mosca & Chen, 2017).

Saliva moistens food, and binds masticated food fragments into a cohesive bolus, and lubricates it to be transported by the tongue to the posterior part of oral cavity. Saliva is produced by three pairs of major (the parotid, submandibular, and sublingual salivary) and minor glands (labial, lingual, buccal, and palatal) (Matsuo, 2000, 2005). The **parotid glands** lie between the skin and the masseter muscle, near the ears. They secrete saliva into the mouth through the parotid duct, which is located near the second upper molar tooth. The **submandibular glands**, which are in the floor of the mouth, secrete saliva into the mouth through the submandibular ducts. The **sublingual glands**, which lie below the tongue, use the lesser sublingual ducts to secrete saliva into the oral cavity (Betts et al, 2017).

The mean flow rate of unstimulated/resting whole saliva in healthy persons during the day is reported in the range of 0.3–0.4 mL/min but with a large standard deviation (Dawes, Pedersen, Villa, Ekströme, Proctor, Vissink, et al., 2015). Salivary flow rate shows a circadian rhythm of high amplitude with peak flow in the late afternoon, while the flow rate is extremely low during sleep, which reduces the need to swallow during that time. Thus, the time of day for saliva collection or flow rate measurement should be specified. The total volume of saliva secreted per day has been estimated to be about 0.6 L (Dawes et al., 2015). Chewing, tastants, aroma stimuli are known to increase the secretion of saliva (salivation). Sour taste (fruits) or umeboshi (salted plum, which is a traditional sour Japanese pickle) enhances the salivation even only by imagination without actual ingestion but only for persons who have experienced that taste before. Neyraud, Prinz, and Dransfield (2003) reported a 10-fold increase in flow rates (from 0.4 to 3.9 g/min) among 10 subjects chewing of a piece of Parafilm for 30 s (Mosca & Chen, 2017).

Salivais essentially (95.5 percent) water. The remaining 4.5 percent is a complex mixture of ions, glycoproteins, enzymes, growth factors, and waste products. Perhaps the most important ingredient in saliva from the perspective of digestion is the enzyme salivary amylase, which initiates the breakdown of carbohydrates. Food does not spend enough time in the mouth to allow all the carbohydrates to break down, but salivary amylase continues acting until it is inactivated by stomach acids. Bicarbonate and phosphate ions function as chemical buffers, maintaining saliva at a pH between 6.35 and 6.85. Salivary mucus helps lubricate food, facilitating movement in the mouth, bolus formation, and swallowing (Betts et al., 2017). Mucins, which are not present in parotid saliva or the secretions of von Ebner’s glands, are heavily glycosylated glycoproteins and the two main ones in saliva are MUC5B and MUC7, the former being of high molecular weight and the latter of much lower molecular weight (Dawes et al., 2015). These mucins form a slimy, viscoelastic coating of all surfaces in the oral cavity and act as an important lubricant between opposing surfaces during such processes as mastication, swallowing and speaking. These three processes are very difficult for patients who have little or no salivary flow because of such conditions as Sjögren’s syndrome, radiotherapeutic damage to the salivary glands or medication- induced salivary gland dysfunction (Dawes et al., 2015).

Important functions of saliva, rheological change of food fragments, viscosity change by dilution, enzymatic breakdown, formation of bolus and lubrication, release of flavour compounds, protection against virus, bacteria and fungi, buffer capacity, protection and repair of the oral mucosa, and dental remineralization are maintained by normal secretion of saliva. When the healthy salivation does not function, caries, oral mucositis, candidiasis, oral infections, chewing disorders will occur, and leading to dysphagia, halitosis, weight loss (Fenoll-Palomares, Muñoz Montagud, Sanchiz, Herreros, Hernández, Mínguez et al., 2004; Matsuo, 2000; Mosca and Chen, 2017; Mosca, Feron, and Chen, 2019; Sarkar, Soltanamadi, Chen, & Stokes, 2021).

Fenoll-Palomares et al. (2004) carried out the study on the relation between the unstimulated salivation and the buffer capacity in 159 healthy adults of 44 years old in average (52 male and 107 female). Buffer capacity is important to maintain the salivary pH, and can be quantified by bicarbonate. Flow rate was found higher for men (0.57 ml/min) than women (0.42 ml/min). Although salivary pH was not significantly different between men and women (6.84 vs 6.77), buffer capacity (bicarbonate concentration) for men (6.63 mM/L) was higher than that for women (5.32 mM/L). As for the effect of age, the salivary flow rate was lower in elderly than in younger subjects, but pH or buffer capacity was not so different. Fenoll-Palomares et al. (2004) studied the unstimulated salivation because it is an accurate way although stimulated saliva represents the secretion during food intake and is useful for study of the functional reserve.

During eating, tastants stimulate taste receptors on the tongue, which send impulses to the superior and inferior salivatory nuclei in the brain stem. These two nuclei then send back parasympathetic impulses through fibers in the glossopharyngeal and facial nerves, which stimulate salivation. Even after swallowing, salivation is increased to cleanse the mouth (Betts et at., 2017).

Even for a short time 5s in the mouth, saliva amylase-induced breakdown of starch was demonstrated by comparing the thickness sensation of starch-based custard and carboxymethyl cellulose based custard. The viscosity-related sensation, melting and thickness together with flavor perception was found affected by amylase (de Wijk, Prinz, Engelen, & Weenen, 2004).

Recently, it was reported that simulated saliva containing α-amylase break the glycosidic bond existing on the peanut oil body based on SDS-PAGE, zeta-potential, and light scattering, and that this effect of breakage persisted in the later intestinal digestion (Wang, Gao, Yang, & Nishinari, 2021).

The role of saliva in food oral processing was schematized at structural level and molecular level as is shown in Figure 10 (Mosca & Chen, 2017).

Fig.10 Interaction of saliva with food in the mouth (Mosca and Chen, 2017)

Since saliva plays a key role in the food oral processing, instrumental study of texture must include saliva. How to incorporate saliva in the experiments is not evident, and this was reviewed recently (Laguna, Fiszman, & Tarrega, 2021).

**3.2 Nervous systems**

The basic rhythm of mastication is given by the central pattern generator, a group of neurons responsible of the central motor command (Lund 1991). This fundamental rhythmic activity is modulated during mastication by peripheral inputs coming from the receptors in the mouth with information on food transformation.

**3.2.1 Neurons responding food stimuli**

Stimuli are received by receptors and transmitted to peripheral neurons and then further transmitted to central nervous system (CNS) via axon and synapse. Transmission of information between neurons is carried out by sequences of spikes, and firing rates are commonly believed to represent the intensity of input stimuli. In electrophysiological experiments *in vitro*, hippocampal neurons demonstrate a vast diversity of firing patterns in response to **depolarizing current injections**. These patterns are referred to by many names, including delayed, adapting, accommodating, interrupted spiking, stuttering, and bursting (Komendantov, Venkadesh, Rees., Wheeler, Hamilton & Ascoli, 2019).

Figure 11 Parts of a Neuron.The major parts of the neuron are labeled on a multipolar neuron from the CNS. (Betts et al, 2017 Anatomy and Physiology p.512)

Methods used in brain science are classified into three categories: functional Magnetic Resonance Imaging (fMRI), Electroencephalograms (EEG) and Functional Near-Infrared Spectroscopy (fNIRS). The fMRI scanner measures blood oxygenation in the brain and exploits the different magnetic properties of oxygenated and deoxygenated blood. EEG gets recordings of the electrical activity of neurons in the brain using electrodes placed on the scalp. fNIRS is a brain imaging technique that (like fMRI) uses hemodynamic responses to indirectly capture neuronal activity (Weber, Fischer & Riedl, 2021).

Fig. 12 Schematic diagram of the taste and olfactory pathways in primates including humans showing how they converge with each other and with visual and other sensory pathways. Hunger modulates the responsiveness of the representations in the orbitofrontal cortex of the taste, smell, texture and sight of food, and the orbitofrontal cortex is where the palatability and pleasantness of food, and its reward value, is represented. VPMpc—ventral posteromedial thalamic nucleus; V1, V2, V4—visual cortical areas. Pregen Cing, pregenual cingulate cortex. For purposes of description, the stages can be described as Tier 1, representing what object is present independently of reward value; Tier 2 in which reward value is represented; and Tier 3 in which decisions between stimuli of different value are taken, and in which value is interfaced to behavioral output systems. A pathway for top-down attentional and cognitive modulation of emotion is shown in purple. Auditory inputs also reach the amygdala (Rolls, 2016; Rolls et al., 2020).

It is important to notice that various stimuli are transferred to orbitofrontal cortex, and that single neurons respond to different combinations of taste, smell, texture, temperature and visual inputs. Experimental animals, rodents and primates have been used to understand the pathways of various stimuli. Signal processing in primates was found more closer to humans. The orbitofrontal cortex which plays an important role in primates and humans is not well developed in rodents (Rolls, 2016; Wise, 2008). Two cortices in the brain, the primary taste cortex and the secondary taste cortex have different functions: The primary taste cortex is in the primate anterior insula and adjoining frontal operculum and has not only taste neurons tuned to salt, sweet, bitter, sour (Rolls, 2016), and umami (typically monosodium glutamate) (Rolls, Critchley, Wakeman, & Mason, 1996), but also other neurons that encode oral somatosensory stimuli including viscosity, fat texture, temperature, and capsaicin (Verhagen, Kadohisa, & Rolls, 2004).

Kadohisa, Verhagen & Rolls (2005) found neurons which respond to stimuli, viscosity, fat, temperature, and taste. Recordings of brain activity were done by tungsten microelectrodes in the amygdala of two rhesus macaques. Responses of an amygdala neuron (bo217) to various stimuli are shown in Fig. 11.

Fig.13 Firing rates of a neuron bo217 to taste, temperature and viscosity. G (1 M glucose), BJ (black currant juice), N (0.1M NaCl), M (0.1 M monosodium glutamate), H (0.01M HCl), and Q (0.001M Quinine HCl) are the taste stimuli. T10–T42 are the temperature stimuli (10, 23, 37, 42℃, respectively). V10–V10,000 are the viscosity stimuli of CMC (carboxymethylcellulose, changing the concentration of a fixed Mw 7 x 105) with the viscosity in cP (=mPas). V1 is water at 23℃. The fat texture stimuli were SiO10, SiO100, SiO1000 (Silicone oil with the viscosity in cP indicated), VO (vegetable oil), CO (coconut oil) and SaO (safflower oil). Cap,10 μM capsaicin; LaA, 0.1 mM lauric acid; LiA, 0.1 mM linoleic acid. This neuron did not respond to fat texture except LiA). The spontaneous firing rate of the neuron (Spon) was estimated from trials in which no stimulus delivery occurred (Kadohisa, Verhagen, & Rolls, 2005b).

Kadohisa et al. (2005a) found that other neurons which were sensitive to viscosity stimuli did not always respond regularly; in some neurons the firing rate increased and then decreased or decreases and then increased. They found another amygdala neuron bk361 which responded only to fat stimuli but not to other stimuli, viscosity, taste, nor temperature (Kadohisa et al. (2005b). They also found thermosensitive neurons responding to the temperature stimuli. Some neurons were found to respond to combinations of viscosity and/or taste and/or gritty and/or capsaicin and/or fat inputs, therefore these authors thought that these combined stimuli providing a rich representation of the sensory properties of food in the mouth, in which particular combinations of the above properties can be represented separately from the components.

Fat-sensitive neurons have been shown to respond not only to fats such as vegetable oil and other fatty oils in the mouth and to substances rich in fat such as cream and chocolate, but also to chemically different substances that have a similar slick or oily texture such as mineral oil (pure hydrocarbon), and silicone oil. Fig.14 shows the evoked neuronal activity (firing rate) of a fat-responsive neuron bo25 as a function of viscosity.

Viscosity (mPas)

Fig.14 Firing rate as a function of viscosity as a stimulus for fat-responsive neuron bo25 in the brain of rhesus macaques. Line indicates responses to CMC (carboxymethyl cellulose) series. Oils evoked significantly higher activity than either spontaneous activity (Spont) or CMC at corresponding apparent viscosities. The spontaneous firing rate of the neuron was estimated from trials in which no stimulus delivery occurred. Lau, lauric acid; Lin, linoleic acid; MO, mineral oil; CO, coconut oil; Saf, safflower oil; VO, vegetable oil; SilO, silicon oil. (Verhagen et al., 2003)

This neuron showed strong and similar responses to all the oils examined, but did not respond to any of viscosity series of CMC below 10,000 mPas, which showed weaker firing rates than the spontaneous value

The firing rate of a viscosity-responsive neuron 291.2 as a function of viscosity as a stimulus is shown in Fig.15.

Fig.15 Firing rate as a function of viscosity as a stimulus for viscosity-responsive neuron 291.2 in the macaque insular primary taste cortex. C10-C10000: carboxymethyl cellulose with the nominal viscosity of 10, 100, 1,000 and 10,000 mPas. v1: water (1 mPas). mo: mineral oil; vo: vegetable oil; sc: single cream. Si280: silicone oil with the viscosity 280 mPas. Li: linoleic acid; La; lauric acid (Rolls, 2020).

Fig.16. (a)The firing rate of a neuron 25 as a function of coefficient of sliding friction as a stimulus. Abbreviations are as in Figs. 14 & 15, and sao, safflower oil; co, coconut oil; Si100, silicone oil with the viscosity 100 mPas (Rolls et al, 2018; Rolls, 2020). (b) Creamy score as a function of friction coefficient of the milk measured at 5N and 10 mms-1 for silicone (Chojnicka-Paszun et al., 2012)

Based on the observed firing rates, fat-responsive neurons were found to be correlated with the coefficient of sliding friction and not with viscosity which reflects food thickness (Rolls, Mills, Norton, Lazidis, & Norton, 2018). The firing rate of a neuron 25 decreases linearly with the coefficient of sliding friction. The relation to viscosity was found much weaker, with the oils producing a larger neuronal response than is predicted linearly (not shown here, see Fig.5b in Rolls, 2020). It was found that there are some neurons which respond to the coefficient of sliding friction but not to the viscosity, other neurons behave in the opposite sense.

The evidence thus indicates that the mechanisms that sense fat and to which these neurons respond are sensing a physical rather than a chemical property of the stimuli (Kadohisa, Rolls, & Verhagen, 2005a, b; Rolls, 2020; Rolls et al, 2018; Verhagen, Kadohisa, & Rolls, 2004; Verhagen, Rolls, & Kadohisa, 2003). Also, the response was found linear or non-linear. For oils and carboxymethyl cellulose solutions, the firing rate of neuron 25 was found linearly increased with decreasing coefficient of sliding friction, while it was not highly correlated with viscosity.

Recently, coefficient of sliding friction was found from 0.773 to 0.208 and the viscosity was from 662 to 3,176 mPa.s for yogurt with different fat content from 0 to 9.9% (Rolls et al, 2020). Rolls et al. (2020) concluded that the coefficient of sliding friction usefully reflected the fat content of the food, and the viscosity did not. This is in line with the recent tribological understanding of lubrication, smoothness and creaminess (Nishinari & Fang, 2018; Stokes, Boehm, & Baier, 2013; Upadhyay, Aktar, & Chen, 2020).

**3.2.2 fMRI**

Since the discovery of the change of MRI (magnetic resonance imaging) near the artery depending on the oxygen saturation in mice by Ogawa (Ogawa, Lee, Kay, Tank, 1990; Ogawa & Sung, 2007), functional MRI has been an important method to study the brain function imaging. Ogawa named the principle as blood oxygen-level-development (BOLD) contrast (Hayashi, Aso, Fujimoto & Hanakawa, 2020). Since this is a non-invasive method, it has been applied to human subjects. To understand the mechanism of brain function, the localization of each function alone is insufficient and the correlation of each site in the brain has been attracting attention thus resulting in the proposal of the connectome which means the wiring diagram of all neurons (Hayashi et al., 2020; Sporns, Tononi, & Kötter, 2005; Yamagata, 2016). Even a typically used small voxel of 55 microliter in size in neuroimaging study contains 5.5 ×106 neurons, 2.2–5.5×1010 synapses, 22 km of dendrites and 220 km of axons. From this, the difficulty to obtain the connectome for humas can be imagined (Logothetis, 2008).

It has been difficult to identify the site in the brain responsible for a specific function, but a huge collaborative work “Human Connectome Project” realized to make a detailed brain map, which is now usable in open access (Glasser, Coalson, Robinson, Hacker, Harwell, Yacoub et al., 2016). Although fMRI is non-invasive, and can be used for humans, and is used widely among neuroscience, it has a limitation.

The study of neuron activity represented by the firing rate is useful to understand the relation between the brain activity and the textural stimuli in rodents and macaques, but the hedonic problem such as palatability and pleasantness of humans cannot be studied by inserting electrodes into the human brain and fMRI seems to be the most suitable method.

Fig.16a shows the activation induced by viscosity stimulus of CMC with different viscosities, 1cP, 50cP and 1000cP. The exact position in the brain is represented by coordinate system developed by Montreal Neurological Institute (MNI). A correlation analysis between fMRI BOLD signal and the viscosity of the stimuli was performed to reveal the area in the human brain representing the viscosity of intraoral stimuli.

**Figure 17a.** Brain areas where activation (as indicated by the BOLD signal) was correlated with stimulus viscosity. Top row, Left, Activations shown bilaterally in a midposterior region of the insular cortex. The sagittal slice shows the anteroposterior extent of the left hemisphere activation marked by the crosshairs. Bottom row, Left, Activations in the anterior insula. The sagittal slice shows the anteroposterior extent of the left hemisphere activation marked by the crosshairs. R, Right; L, Left. (de Araujo & Rolls, 2004).

**Figure 17b.** Top row,Scatter plot showing the BOLD signal (percentage change) in this region with respect to viscosity produced by the CMC series.

Bottom row, Scatter plot showing the BOLD signal in this region as a function of oral viscosity produced by the CMC series.

L, Left (de Araujo & Rolls, 2004).

As is well known, the relation between the sensorily evaluated thickness and instrumentally observed viscosity was represented by a power law. Fig.15b shows that the BOLD signal change is proportional to the sensorily evaluated viscosity.

Rolls (2020) expected that the sensing of the coefficient of sliding friction for semi-solid foods in the mouth by the fat selective neurons is likely to provide a reliable guide to the fat content of semisolid as well as liquid foods. Rolls and his coworkers applied functional magnetic resonance imaging (fMRI) to study the brain function (Rolls, 2016, 2020). The BOLD (% change) was found to be proportional to the log(viscosity) produced by CMC with different concentrations (Fig.14). This is consistent with the previous findings of this research group (Kadohisa et al, 2004) and this is also widely recognized in psychophysics (Nishinari et al., 2018).

The sensory characteristics of fat has been shown to be correlated with the viscosity (Mela, Langley & Martin, 1994; Li, Joyner, Carter &Drake, 2018), some group affirmed that the fat is the sixth taste, *oleogustus* (Mattes, 2021). While both physical and chemical factors are important to understand the whole aspects of fat, de Araujo et al (2004b) stated that not only the viscosity but some other factor play a key role in the fat sensation because some single neurons in the orbitofrontal cortex respond to fat but not to carboxymethyl cellulose, which they believe purely viscous without no taste, and that other neurons respond to carboxymethyl cellulose but not to fat (Verhagen et al., 2003).

**Figure 18.** Responses to the oral delivery of fat as assessed by the comparison (fat-control). Activations were observed in the mid-insula and hypothalamus (Hy) (top row, left), anterior insula (top row, middle), and anterior cingulate cortex (top row, right). The average time course data (across trials and subjects) from the mid-insular cortex (from the voxels marked by the crosshairs in the top row, left) are shown in the bottom row for the conditions fat and CMC 50 mPas. R, Right (de Araujo et al., 2004; Rolls, 2020).

Fig. 17 shows the fMRI results representing the brain activity during drinking of vanilla- or strawberry- flavored dairy drink with high or low-fat content (Grabenhorst, Rolls, Parris & d’Souza, 2010; Rolls, 2020). The sensory evaluation showed that the texture of the high-fat stimulus was rated as more pleasant than the low-fat stimulus for each of the 2 flavors. As for the pleasantness of flavor, vanilla was rated higher than strawberry probably because of the quality of the artificial strawberry flavor was not so high (Prof. Rolls was thanked for this information).

Fig. 19 Brain regions which respond to a stimulus (fat texture) when a human subject was given a high-fat dairy drink with vanilla or strawberry flavor (a)The left region is the sagittal section and the right region is the coronal section. Yellow circle (only one in the right section) represents the midorbitofrontal cortex (MOFC), and a pink circle (one in the left section and another in the right section) stands for the anterior cingulate cortex (ACC). (b)The relation between the percentage change in the BOLD and the rating of the pleasantness of texture in ACC (pink circle). The negative values (4 open circles) are obtained from strawberry- flavored drink while the positive values (8 open circles) are from vanilla-flavored dairy drink. (c)The relation between BOLD and the pleasantness of texture in MOFC (yellow circle). The negative values of the peasantness (4 open circles) are obtained from strawberry- flavored high and low fat dairy drink while the positive values ( 8 open circles) are from vanilla-flavored high and low fat dairy drink. The colored vertical bar in the right shows z statistical value for the analysis illustrated in the brain slices. (Grabenhorst et al, 2010; Rolls, 2020).

These experimental findings that the BOLD change is highly correlated with pleasantness of fat texture suggest that the oral fat texture is represented in the midorbitofrontal cortex and the anterior cingulate cortex (Rolls, 2020). This assignment of the site was confirmed by additional data showing that this region is involved in representations of fat texture because it was activated more by high-fat than by low-fat stimuli (data not shown, See Fig.2d, f in Grabenhorst et al, 2010). Interestingly, activations in the same region was also found to be correlated with the ratings of the pleasantness of flavor (data not shown, See Figure 3a,c. in Grabenhorst et al, 2010). This may be a clue to understand the interaction between the texture and flavor perception.

**3.3 Instrumental simulation of mastication**

As discussed above, the physiological and psychological aspects are very important in the texture sensation, and the best and only way to evaluate the texture together with palatability is the sensory evaluation by human subjects. But, the reproducibility and the individual difference are very difficult problems and in addition it takes a time and cost to train the panel.

Since it takes a time to train the panel, and it is difficult to get a good reproducibility in the sensory evaluation, there have been many trials to use a mastication simulator. In the early stage of the texture studies, Bourne (2002) developed the uniaxial compression as a simple and reproducible method of the determination of textural attributes (Nishinari and Fang, 2018). The effort to improve the method has been done (Lu, Xu, & Li, 2017; Meullenet, & Gandhapuneni, 2006; Mishellany-Dutour et al, 2011; Morell, Hernando, & Fiszman, 2014; Panda, Chen, Benjamin, 2020; Peyron, Santé-Lhoutellier, Dardevet, Hennequin, Rémond, François, et al., 2019; Peyron, & Woda, 2016; Shibata, Takahashi, Nagahata, Kimura, Shimizu, Hotta et al., 2019).

It is necessary to mimic the mastication precisely, but it was difficult to analyze the complex deformation and fracture mode which is not a simple uniaxial compression but a mixed mode of compression and shear. In addition, it is necessary to introduce artificial saliva to analyze the stickiness or adhesiveness of dried foods such as biscuits or potato chips if not these textural attribute turned out to be zero as was reported in some papers, but it is evidently wrong. In a mastication simulator proposed by Mishellany-Dutour et al. (2011), artificial saliva supplying unit was incorporated. The mastication behavior may be influenced by aroma which in turn may affect taste and texture, and the gas collection unit is incorporated in a mouth simulator proposed by Salles et al. (2007). Simpler artificial mouth models focusing mainly on the aroma release, and sophisticated instruments for flavor analysis will be described in the second part of the paper.

Fig. 20. Schematic representation of the AM2 artificial masticator with insert of an open view of the mastication chamber in which the fixed and mobile masticatory disks are shown. The whole apparatus is 130 cm long and 30 cm in height. The masticatory chamber (19.5×9.5 cm) is located in the continuation of the shaft holding the mobile masticatory disk (Peyron et al., 2019)

The research group of Peyron and Woda has proposed a masticator AM2 consisting of masticatory disks, a mobile masticatory disk acting as the mandible and a fixed masticatory disk acting as the maxilla (Fig.16). The mobile masticatory disk compresses and shears the food against the fixed masticatory disk, which can be achieved by rotating the mobile masticatory disk. This movement is achieved by the tongue in vivo. The force was monitored by a spring with varying strengths behind the fixed disk.

The cumulative particle distribution curves are used to compare food boluses obtained in vivo and in vitro (Fig.17).

Fig. 21. Example of AM2 programming for meat mastication. Mean particle size distribution curves are expressed as cumulative weight percentages of particles passing through each sieve during manual sieving. The force generated for food compression during mastication depends on the stiffness of the spring which must be chosen as a function of food resistance. The curve obtained with the spring 3 (18.2 N/mm of spring stiffness; n=4) and 22 masticatory cycles gave the best fit with the mean in vivo curve (n=8). Spring 3 with only 20 cycles gave a higher median value (= d50, theoretical sieve letting pass 50% particle mass), indicating a poorly prepared food bolus with larger particles (n=4). Spring 4 (23.5 N/mm of spring stiffness) was harder and gave a lower d50 value when used with 22 masticatory cycles, indicating excess in food bolus disruption (n=4). For the sake of readability, standard deviations are not drawn (Peyron et al., 2019)

The cumulative particle distribution curve for 22 masticatory cycles in vitro using a spring 3 with stiffness 18.2 mN/mm (black filled circles on solid line) coincided well with the curve obtained in vivo with 22 masticatory cycles (black filled circles on dashed line). The cumulative particle distribution curve for 22 masticatory cycles in vitro using a spring 4 with stiffness 23.5 mN/mm (gray solid triangles on solid line) gave rise to overly disrupted meat bolus (d50 ~ 2.8 mm). On the other hand, the curve for 20 masticatory cycles in vitro using a spring 3 (gray solid squares on solid line) produced large particles (d50 ~ 5.4 mm) indicating that this instrumental mastication was not sufficient to mimic the in vivo mastication.

The research group of Higashimori has developed a method to detect and analyze the pressure distribution when the food is compressed. Since it has been reported that soft gels are squeezed between the tongue and hard palate without using teeth, and that humans change the strategy of breakdown method from the tongue alone to the teeth (Ishihara, Isono, Nakao, Nakauma, Funami, Hori, et al., 2014; Ishihara, Nakao, Nakauma, Funami, Hori, Ono, et al. , 2013; Nishinari, Ishihara, Hori and Fang, 2020), a food gel on the artificial tongue was uniaxially compressed by a sheet sensor fixed to the rigid plate to observe the pressure distribution as shown in Fig.22 (Shibata, Ikegami, Nakao, Ishihara, Nakauma, and Higashimori, 2016).

Fig.22 Texture sensing system for a soft gel food. The gel food sample is compressed between the imitation tongue and the movable upper plate, and fractured, and the pressure distribution ***P*** is measured as time-series data (Shibata et al, 2016) .

The pressure distribution data of gel foods with different values of sensory evaluation are collected. First, the feature vector ***x*** *=* (*x*1, *x*2, ,, *x*i, ,, *x*n)T (superscript T indicates the transpose in the matrix algebra) is extracted from the pressure distribution data ***P*** through image texture analysis. Then, the principal component vector ***y*** *=* (*y*1, *y*2, ,, *y*i, ,, *y*n)T is calculated. The value of sensory evaluation of the i-th texture attribute is written as *n*i, such as elasticity (i = 1), smoothness (i = 2), stickiness (i= 3), and granularity (i=4). The definition of these sensory attributes are as follows: *Elasticity:* the impression of a gel’s extension and the extent to which

it pushed back the tongue before fracture. *Smoothness:* the impression of smoothness at the surface of the gel before fracture. *Stickiness:* the impression of difficulty in spreading the gel after fracture. *Granularity:* the impression of granularity at the surface of gel after fracture.

This value of sensory evaluation *n*i= *f**i*(***y***) is derived by building a multiple linear regression model with the principal component vector ***y*** as its predictor variable and the value of sensory evaluation *ni* as its response variable. By substituting the pressure distribution data ***P*** of an unknown gel food in the estimation equation, the value of sensory evaluation *ni* of texture term *i* is estimated (Shibata et al, 2016). In the construction and verification of the prediction model, leave one out cross validation method was used, which has been applied successfully for various products (Arlot, and Celisse, 2010).

Taking into account the reported value of the elastic modulus of the human tongue 1.22 ± 0.42 × 104 Pa in a relaxed state and 12.25 ± 5.85 × 104 Pa in a tension state, artificial tongue mimicking a relaxed state and a tension state could be prepared (See 3.1.4 Tongue). Figs.19 (a), (b), and (c) show the pressure distribution during compression at different stages, 1.5 s, 3.0 s, and 4.5 s. As shown in Fig. 23(a), the pressure on the relaxed imitation tongue (*t* = 1*.*5 s) increased slowly. This is because the surface of the tongue passively deformed as concave surface. The pressure increased with time, but the gel was not fractured even at final stage (*t* = 4*.*5 s). For the imitation

Fig. 23 The top photos show a compression-fracture test of a gel food, where the imitation tongue is in the relaxed state corresponding Fig.19(a) is used. In this case, the gel food sinks into the imitation tongue and the condition of the gel food cannot be visually confirmed. Pressure distribution during the compression-fracture test of the gel food at different compression stages 1.5, 3.0 and 4.5 s at a compression speed 2.0 mm/s. (a) Relaxed imitation tongue. Some (b) Contracted imitation tongue. (c) Rigid base. Pressure scale is indicated on the left of Fig. 19(a). With increasing pixel color from white to black, the pressure value increases.

tongue stiffer at the contracted state, the pressure increased faster and the gel was fractured at the final stage *t* = 4.5 s (Fig.19(b) right). When the rigid base was used, the pressure increased faster and the food gel fractured earlier at *t* = 3.0 s (Fig. 19(c) middle). The accuracy of the texture estimation was evaluated by the coefficient of determination *R*2. The average value of the four texture terms *R*2 was the maximum (= 0.80) when the contracted imitation tongue was used. However, for Elasticity *R*2 was the maximum when the relaxed imitation tongue was used. Shibata et al. (2016) speculated that humans might improve the sensitivity for “*Elasticity*” by relaxing the tongue muscle so that its passive deformation became large. The relaxed imitation tongue too might reproduce such an effect.

Nakauma, Ikegami, Funami, Shibata and Higashimori (2021) examined the relation of instrumental evaluation and sensory evaluation using 15 kinds of aqueous polysaccharide gels with sugars, calcium lactate, potassium chloride and 8 kinds of emulsion gels with palm oil, skimmed milk, glycerides. Four sensory texture terms were selected: *tsurutsuru* (slippery smoothness of the surface), *mochimochi* (soft, deformable and pushing back the tongue) before fracture, and *nettori* (adhere to the surface of oral cavity, difficult to extend and gather together), *zarazara* (gritty particle sensation in the oral cavity) after fracture. Sensory evaluation was performed for both model prepared gels both 15 aqueous gels and 8 emulsion gels to construct the prediction model. The correlation between the sensory evaluated four attributes for commercially sold 5 aqueous type jellies and 3 custard type puddings were well correlated with the constructed prediction model based on multiple regression. It was found that two afterfeelings *nettori* (adhering the oral surface) and *zarazara* (gritty particle sensation) were influenced by the oil spreading.

To extend this method of texture sensing system to harder solids such as doughnuts which are chewed by teeth, Higashimori’s group incorporated artificial teeth (Shibata et al., 2019). Six different types of commercially available old-fashioned doughnut, A–F, were tested. Four texture terms, *crispiness* (*i* = 1), *crumbliness* (*i* = 2), *gooeyness* (*i* = 3), and *meltiness* (*i* = 4), were considered. *Crispiness* is the impression that the bolus touches the teeth. *Crumbliness* is the impression that the bolus collapses. *Gooeyness* is the impression that the bolus clings to the mouth. *Meltiness* is the impression that the bolus mixes with saliva and quickly disappears from the mouth. Five trained panelists participated in this experiment. Taking into account the temporal change of the texture sensing, the mastication process was divided into four periods: preparation period (0 ≤ *t* ≤ 5 s), mastication period I (5 ≤ *t* ≤ 20 s), mastication period II (20 ≤ *t* ≤ 35 s), and mastication period III (35 ≤ *t* ≤ 50 s). In this experiment, artificial food boluses I–III (Bolus I–III), which reproduced the state of the bolus during mastication periods I–III, respectively, were used. Shibata et al. (2019) obtained a higher coefficient of determination *R*2 by incorporating the analysis of bite force in addition to the tongue pressure. They are aiming to make a robotic simulator enabling a food bolus so that they can get spatiotemporal data during the bolus formation. Thus, they could get a better coefficient of determination *R*2.

**Objective measurement of texture**

If the texture is a sensory property as Szczesniak said in her latest review in 2002, it cannot be measured by instruments. However, since the sensory evaluation cannot be done with high reproducibility even for one person, and the individual difference among panelists are always found, instrumental measurements of the texture has been pursued, and a plethora of papers have been published. Since the so-called texture profile analysis (TPA) is an easy experiment, it has been applied to many kinds of foods. The hardness, adhesiveness, cohesiveness and other parameters have been reported. Bourne has raised some examples in his textbook (2002) and the good correlation between the sensory evaluation and the instrument measurement for the hardness of cheese by Shama and Sherman (1973) was found only when the degree of compression and the compression speed were in the certain range. The sensory judgement of the hardness did not coincide with the instrumental compression with slow compression speed (<20 cm/min) and with lower degree of compression (<30%). As this example shows, if the instrumental measurement is done to find a good correlation with sensory evaluation, the compression speed should be chosen carefully. However, even today, many TPA test results conducted at slow compression speed were compared with sensory evaluation. Another obvious point to be taken into account is that the adhesiveness parameter of dried foods, e.g., biscuits, should be evaluated in the presence of saliva. Without saliva, the negative force or energy, corresponding to the adhesiveness, which appears during raising of plunger cannot be detected, although everybody knows that biscuits show some adhesiveness during mastication.

Since the individual difference among panellists causes a difficulty, and it is time consuming to build up the trained panel, and even after training the problem of adaptation and fatigue could not be overcome completely, and thus many apparatuses or models of artificial mouth which mimic better the food oral processing (Panda, Chen, & Benjamin, 2020; Peyron, & Woda, 2016; Peyron, Santé-Lhoutellier, Dardevet, Hennequin, Rémond, François, & Woda, 2019; Sarkar, and Krop, 2019; Rudge, Scholten, & Dijksman, 2019). The great advantage of artificial/model mouth is that the good reproducibility is ascertained, and the problem of fatigue and adaptation can be avoided. While human mastication is influenced by the taste and odor of ingested foods, artificial/model mouth does not take into account this.

**3.4 Virtual reality approach**

**3.4.1 Thermal**

Yoshida and Ogawa (2018) showed a possibility to modify the sensation of spiciness using a tongue stimulator comprising of interlaced warm and cool bars. This is based on the knowledge that the spiciness is related to the pain which is perceived through Transient Receptor Potential Channel (Tominaga, 2013; Tominaga, et al., 1998). Subjects touch their tongue on the tongue stimulator and perceived spiciness became strongest when the temperature difference is 30 deg Celsius. This stimulator is expected to be helpful for patients who like spicy foods but the intake was limited because of the adverse effects induced by the excessive intake.

**3.4.2 Visual**

Many paste type foods have been produced aiming to prevent the choking and aspiration for disadvantaged persons, however, most of these don’t seem to be attractive and thus these people lose the appetite. Enzymatically treated meat, fish, vegetables keep the original shape and color, and look appealing. It shows the importance of appearance. The appearance plays an important role in Japanese cuisine, “*washoku*”, and the Japanese traditional dietary cultures was registered as a UNESCO Intangible Cultural Heritage in December 2013”. The beauty of nature in the presentation, plates decorated with leaves, flowers and bamboo, and natural motifs are represented in decoratively cut foodstuff. Decorating tables and rooms with objects matched to the season are also closely associated with *washoku* (Nishinari, Fang, Mleko and Tomczyńska-Mleko, 2016; Nishinari and Ooizumi, 2021). The importance of the appearance is also recognized in all over the world (Delwiche, 2012; Piqueras-Fiszman, & Spence, 2014; Wadhera, & Capaldi-Phillips, 2014).

 Whether visual perception processing is facilitated or not has been examined by measuring the time needed for perceiving the digitally printed form of the numbers 2 and 5 rotated 90 degree rotation (Lupyan and Spivey, 2008). The panelist group instructed that these are symbols and their task was to identify the different symbol (2) among other symbols (5). The other group was instructed that these are the numbers 2 and 5 rotated clockwise ( and ). The experimental results showed that the time required for the identification of 2 surrounded or buried in many 5 was much shorter for the group instructed that these were numbers than the group instructed that these were mere symbols with no meaning.

To understand the effects of visual food perception on the mastication and swallowing, the changes in oxygenated hemoglobin concentrations (Oxy-Hb) in the prefrontal cortex was monitored by near infrared topography (NIRS) (Kamiya, et al., 2015). Subjects were shown images of both normal food and blenderized normal food with paste like appearance on an i-Pad. Oxy-Hb levels were found significantly higher with normal food than with blenderized food ( p＜ 0.05). It was thought that the projection pathway from the amygdala to the prefrontal cortex might be activated by visual stimulus but, the reliability was low. These authors further performed the repetitive saliva swallowing test (RSST) and measured salivary amylase activity. RSST was found reliable by comparison with VF test (Oguchi et al., 2000). RSST values were significantly higher with normal food than with blenderized food (p＜0.01), with high reliability (ICC＝0.62), suggesting that the appearance of normal food increased saliva secretion and enhanced swallowing reflex. There were no significant differences in salivary amylase activity values, with low reproducibility.

**3.4.3 Auditory- crispness and crunchiness**

Another method to improve the texture feeling has been pursued via modifying the sound. Zampini and Spence (2004) studied the effects of sound on the perceived sensation of crispness using potato chips (called crisps in UK). Subjects were fed back the sounds, recorded by a microphone, via pair of headphones during biting potato chips. Their results showed that potato chips were evaluated fresher and crisper when the overall sound level was increased and/or when the high frequency component (2kHz -20kHz) of the biting sounds were amplified. This work brought the authors an Ig Nobel Prize (Nutrition) in 2008.

As is well known, the perceived sound through air-conduction and bone-conduction coexist in the natural biting (Vickers and Bourne, 1976; Wang et al, 2020). Sound perceptions for dry crisp foods and wet crisp foods are expected to be different. Effects of sound modulation during eating of apples on crispness was evaluated (Demattè, Pojer, Endrizzi, Corollaro, Betta, Aprea, et al., 2014). Reducing the high frequency component of the sound made the subjects evaluate apples less crispy and harder. It should be noticed that the attribute hardness which is believed to be perceived by mechanoreceptors is influenced by the auditory sensation, which is the result of the cross-modal interactions.

Koizumi, Tanaka, Uema, & Inami (2013) using six foods, potato chips, cracker, senbei (rice cracker), almond, *karinto* (rice cracker coated with non-refined sugar), and *daifukumochi* (sweetened red beans wrapped with sticky rice cake). Subjects were introduced the sounds, which were recorded by a microphone set at the lower jaw during mastication beforehand, in synchronization with the motion of the subject’s mastication when they bite one of the above foods. When the introduced sound was treated through high pass filter, potato chips were perceived fresher than by the sound treated through low pass filter. As for a cracker, the introduction of non-filtered recorded sounds led to the increase in perceived thickness of the cracker.

Puréed or minced foods were evaluated by 30 elderly subjects with no dental or auditory dysfunction (Endo, Ino & Fujisaki, 2016). The following five nursing care foods were used: 1) Five spicy fried and boiled vegetables (*Go-shu-yasai-no-kinpirani*), 2) Pumpkin simmered with minced chicken (*Kabocha-no-tori-soboroni*), 3) Japanese radish simmered with minced chicken (*Daikon-no-tori-soboroan*), 4) Meat and potato stew (*Nikujaga*), 5) Shrimp and scallop with cream sauce (*Ebi-to-kaibashira-no-kurimuni*). Panellists felt mismatching between crunchy pseudo-chewing sound and two test sample foods 2) and 4) because these foods do not emit sounds. In spite of this, panellists perceived greater stiffness and roughness in response to crunchy chewing sound for all foods tested. In addition, chemical taste such as heavy/light or insipid/rich were not found to be affected by sound. This was not in agreement with a general comment of Spence who advocates that sound influences greatly the flavour (Spence, 2015). Endo, Ino and Fujisaki (2017) further examined the effect of pseudo-chewing sound from the view point of the inhomogeneity using minced foods and puréed foods. The following three foods in minced state and pureed state were used. 1) *Kinpira* (spicy fried chopped burdock and carrot). 2) *Gomoku-mame* (Soybeans simmered with vegetables [carrot, burdock, shiitake mushroom, and *konbu* [tangle weed]), 3) *Chikuzen-ni* (Vegetables [burdock, carrot, lotus root, and bamboo shoot] simmered with minced chicken). Sound effects on perception during eating were examined with or without hearing crunchy pseudo-chewing sound. They confirm the similar tendency as in the previous work, and in addition, they found that the enhancing the intensity of perceived texture by virtue of pseudo-chewing sound was more effective for inhomogeneous food (minced) than for homogeneous foods (puréed).

Endo, Kaneko, Ino & Fujisaki (2017) examined the congruity and similarity between the pseudo-chewing sound and the actual chewing sounds. They chose two nursing care Japanese pickles (*shibazuke* (cucumber pickles) and *Tsubozuke* (Japanese radish pickles) which were cooked to be soft enough so that they could be mashed between the tongue and the palate. Two other dry foods, rice cracker and cookie were also used as test samples. Ten healthy subjects participated the test, and each subject was instructed to chew two samples intermittently hearing one of six pseudo-chewing sounds. Six pseudo-chewing sounds used were noisy chewing sounds, EMG chewing sounds (reproduced from the recorded signals during mastication by electromyography), four sounds generated from chewing the above two pickles, rice crackers, and cookies. It was found that when the pseudo-chewing sound was felt similar to the chewing sound of the actually chewed sample, the combination of the pseudo-chewing sound and the sample food was felt more natural. However, although the pseudo-chewing sounds of rice cracker and Japanese pickles were not very similar, subjects felt the combination of these two relatively natural. The authors concluded that it is necessary to create pseudo-chewing sounds closer to actual sounds of chewing, which hopefully giving the chewy sensation to improve the appetite of disadvantaged persons who are obliged to accept only texture modified soft foods such as purees and pastes.

Since it is necessary to make pseudo-chewing sound resemble closely the actual chewing sound, Kaneko, Endo & Ino (2020) measured masseter EMGs and mastication sounds simultaneously. They found that actual chewing sound decreased with increasing number of strokes. They also found that the difference between the duration and amplitude of sound detected in the actual chewing of rice crackers and Japanese pickles was smaller than the difference induced by the number of strokes. The decrease in the actual chewing sound within a few strokes is consistent with previous finding of Peyron, Lassauzay, and Woda (2002) who reported that hardness of the bolus decreased during initial stage and little changed after further strokes. Taking into account of these, they obtained a better mimicking pseudo-chewing sound.

**4.** **Food oral processing**

　A process model of Hutchings and Lillford (1988) has been used as a starting point to understand the processing of a food from the ingestion to swallowing. A cooked meat with a strong structure must be broken down by teeth, and mixed with saliva and is transformed to a swallowable bolus. This process depends on the moisture content in the food. A sponge cake having a weak structure still needs a mastication during which it is broken down and mixed with saliva to be lubricated before being swallowed. A raw oyster or beverages can be swallowed immediately. The structure of most foods will monotonously be weakened. A well-known example is the enzymatic degradation of starchy foods leading to the decrease in viscosity even in a very short time. Comparing the viscosity change of starch-based custard induced by the action of amylase and acarbose, de Wijk, Prinz, Engelen, & Weenen (2004) concluded that the perceived thinning was due to the amylase-induced breakdown of starch. Recently, it was found that the viscosity change could occur not only in starchy-based foods but also in oily foods. Natural oil body (OB) has been attracting much attention because of its technological functional role in food processing and used as a natural emulsifier. Wang, Gao, Yang and Nishinari (2021) reported that α-amylase in saliva could break the glycosidic bonds on the surface of OB, promoting the later digestion of the OBs in the gastric and intestinal environments.

Fig. 24 After ingestion of food (sesame paste) into the mouth, it is masticated into smaller pieces losing its “degree of structure” and mixed with saliva thus increasing the “degree of lubrication.” Food is swallowed after reaching these two thresholds and the rectangle represents a “swallowing bar (box)” where the two thresholds have been reached (Nishinari et al, 2019).

However, the structure of some pastes can be strengthened in the early stage of oral processing as shown in Fig.20 (Nishinari, Fang and Rosenthal, 2019). The “structure” of sesame paste increased to a certain degree when it absorbs a small amount of water, and then further water absorption weakens the structure (Rosenthal, & Yilmaz, 2015).

**4.1 Breakdown process of ingested foods**

**Mouth process**

When the mouth process model was proposed by Hutchings and Lillford in 1988, it was not so well known, but after the first food summit conference held in 1999 in Wageningen, this model has been attracting much attention. To understand better and more precisely the process, Prinz and Lucas (1997) and Hiiemae and Palmer (1999) discussed more details of the mastication and swallowing process (Nishinari and Fang, 2018; Nishinari, Ishihara, Hori and Fang, 2020).

Hiiemae and Palmer (1999) proposed a more detailed model for oral processing. They could analyze the barium-infused food movement and also the tongue movement by radiopaque markers in the oral cavity detected by VF. However, the quantitative analysis of tongue movement was technically irreconcilable with documentation of food position and movement because the addition of barium to the food obscures the position of markers on the tongue surface. VF recording is also constrained by restricting to 5 min per lifetime per subject.

The duration of each stage in the oral processing sequence was analyzed by Hiiemae and Palmer (1999) as follows:

Stage I transport: The time the food crossed the incisors (start maximum gape) until hard foods (the first tooth–food–tooth contact occurred, determined visually and from rate changes in the jaw movement profile) or soft foods was disrupted. (Tooth–food–tooth contact: The moment during jaw closing when the food positioned on the occlusal surfaces of the lower teeth first makes contact with the occlusal surfaces of the upper teeth as the jaws close).

Processing: From the end of Stage I until the initiation of Stage II transport in which food is broken down by chewing, processed by the tongue acting against the hard palate, or both.

Stage II transport: defined as beginning at the time food was clearly detected distal to the fauces, that is, between the soft palate and the pharyngeal surface of the tongue. It is important to reemphasize that processing and Stage II can occur concurrently, that is, food is processed

as triturated food accumulates to form a bolus.

HTT: Hypopharyngeal transit time, that is, the time elapsed from the moment the leading edge of the bolus leaves the valleculae to the time the trailing edge enters the esophagus. HHT1 refers to HHT of the first swallow, and HHT2 refers to HHT of the second swallow. The second subsequence began immediately after the first swallow; the second swallow occurred at the end of the second subsequence. This definition of HTT1 and HTT2 was not described in Hiiemae and Palmer (1999). Authors would like to thank Prof. Palmer for the clarification.

Fig. 25 The duration (mean ± SD) for each component of the feeding sequence for all subjects and each food. Initial food consistency affects the duration of processing (process), Stage II transport with processing (oropharyngeal aggregation time; OPAT) and the second subsequence (S-S2) but with neither Stage I transport nor the duration of hypopharyngeal transit time. HHT1 refers to HHT of the first swallow, and HHT2 refers to HHT of the second swallow. The second subsequence began immediately after the first swallow; the second swallow occurred at the end of the second subsequence. First subsequence: n =10 for chicken spread, banana and cookie, 6 for peanuts; second subsequence: n = 9 for chicken spread and cookie, 5 for peanuts. No attempt was made to distinguish processing or OPAT in S-S2 given the variability of behavior observed (Hiiemae & Palmer, 1999)

The duration of each stage in the oral processing of four foods with different textures, chicken spread, banana, cookie, and peanuts is shown in Figure 21. As can be seen clearly, the duration for Stage 1, HTT1 and HTT2 were not so different for soft foods (banana and chicken spread) and for hard foods (cookie and peanuts) although total sequence durations differed with food type, with peanuts and cookie being significantly longer (p<.0001) than banana or chicken spread. The hardness of foods influenced strongly on the duration for Processing and OPAT; harder foods show longer duration.

The important finding of Hiiemae and Palmer (1999) is that triturated food is accumulated on the pharyngeal surface of the tongue for a considerable percentage of the total time from the beginning of the oral processing to the initiation of the first HTT (HTT1) for a bolus. Matsuo and Palmer (2009) noted that oral preparatory phase (food processing) and oral propulsive phase (Stage II transport and bolus aggregation) can overlap in time. After a variable period of elapsed

time, the pharyngeal bolus is swallowed. As shown in Figure 21, both the time HTT1 and HTT2 are not so different for four foods with different textures, which may suggest that the bolus that is ready to enter the esophagus have similar textures. It means that the initial textural differences are obliterated just before the swallowing.

The number of Stage II transport cycles, duration of processing (from food entering the mouth to onset of swallowing), pre-upper esophageal sphincter (UES) transit duration (from onset of swallowing to onset of UES transit), UES transit duration (leading edge to trailing edge passing the UES), and total sequence duration (from onset of swallowing to terminal swallow) were measured by VF during eating 6-g squares of banana, tofu, and cookies by13 healthy subjects (Hiraoka, Palmer, Brodsky, Yoda, Inokuchi, & Tsubahara, 2017). It was found that all four durations were positively correlated with the number of Stage II transport cycles. Principal component analysis revealed two orthogonal principal components related with timing variables and the number of swallows. Hiraoka et al (2017) concluded that food transit duration was longer with harder foods before processing and more viscous foods just before swallowing.

Yokoyama et al (2014) conducted a tongue-squeezing examination of soft jellies with different hardness and found that bolus texture just before swallowing may differ among each jelly irrespective of tongue pressure modulation during size reduction, and such differences require the modulation of swallowing pressure. The influence of food texture on each stage of FOP and the interrelation between each stages of mastication behavior should be further studied.

To capture the temporal change of the mouthfeel characteristics, texture, aroma and taste, the temporal dominance sensation (TDS) method was proposed. Each of these characteristics interacting each other and cannot be analyzed separately, but the analysis of each elementary process can be a basis of the complete understanding of the whole process. Stokes, Boehm and Baier (2013) proposed to divide the oral processing process into 6 stages: (i) first bite, (ii) comminution, (iii) granulation, (iv) bolus formation, (v) swallow and (vi) residue, as shown in Figure 22.

Figure 26. Six stages in the oral processing of solid food. Although some stages occur simultaneously, more detailed analysis of each elementary process can be done by this division (Stokes et al., 2013).

**4.1.1 Selection and breakage**

When a matter is recognized as a safe and appetitive food by visual, and olfactory sensation, it is ingested in the mouth. After this first selection, the second selection in the oral cavity begins. At first, the solid food must be put between teeth and after the first bite, a broken part must again be put between teeth. It is intuitively and logically evident that a larger portion should be selected for the second bite, and this probability being put between teeth is quantitatively represented by a selective function S(*X*), where *X* stands for the particle size. It is expected that *S*(*X*) is an increasing function of *X*, and indeed based on human experiments it was found that a parabolic function fitted well:

*S*(*X*) = *vXw*(1)

(van der Bilt, Olthoff, van der Glas, van der Weelen & Bosman, 1987; T. Liu, Wang, Chen, & van der Glass, 2018; H. Liu, Wang, Chen, & van der Glass, 2020). Then, each particle will be fragmented into the same number of fragments in the same ratio of sizes regardless of the initial size of the particle. The weight fractions of the fragments of a particle of initial size *X*0 was assumed by a cumulative distribution function

*B*(*X*) = 1 - (l +*rX*/*X*0)(l -*X/X*0)*r* (2)

where the breakage *B*(*X*) is the weight fraction of selected particles of initial size *x*0, which break into particles smaller than size *X*, and *r* is related to the degree of fragmentation. The value of *r* increases as fragmentation increases, but is assumed to be independent of initial particle size (van der Bilt et al., 1987).

These authors used Optosil (silicone rubber commonly used as a dental impression material) with an edge length of 8mm as a test food. After chewing a fixed number of strokes, *N*, the particle-size distribution of the chewed food was determined by sieving. In different experiments, the number of chewing strokes ranged between 10 and 120 cycles.

Cumulative weight-percentage undersize as a function of the sieve aperture is shown in Fig.23. This was obtained for test food Optosil, but a similar figure was also obtained using peanut (See Fig.1 in Olthoff et al., 1984).

Fig. 27. Cumulative weight-fraction undersize  as a function of the logarithm of the sieve aperture *x* (mm) for individual 7 after various numbers of chewing strokes 10, 20, 40, 80 and 120. Drawn lines are best fits through the data points according to equation (1) (van der Bilt et al., 1987).

All the experimental data were found well fitted by a Rosin-Rammler distribution function

= (3),

where is the weight fraction of particles with a size smaller than *X*, and the median *X*50 is

the aperture of a theoretical sieve through which 50 % of the weight can pass, and *b*, the broadness, indicates the extent to which the particles are equally sized (T. Liu, et al., 2018; H. Liu, et al., 2020). The curves tend to be steeper with increasing values of *b* indicating that the particle sizes distribution is less broad.

The particle-size distribution cannot be fitted successfully for the initial stage of chewing because hardly any particles have been broken and all the particles are about the same size, which gives a step-like function as shown in Figs. 1 and 2 of Liu, Wang, Chen, & van der Glass, (2018) for chewing cycles *N* = 3. However, good fits could be obtained after chewing at least ten times as had been observed in (Olthoff *et al.,* 1984).

The median particle size, *x*50, decreases as a function of the number of chewing cycles *N*

according to the relation:

*X*50 (*N*) = c · *N*-d (4)

The variable *c* defines the notional median particle size after one chewing stroke. This value is only theoretical because relevant data for *X*50 can only be observed after at least ten chewing cycles. The double logarithmic plots of *X*50 and *N* is show in Fig. 24 obtained from a similar experiment using also cube-shaped Optosil test food (T. Liu, et al., 2018). Test foods, Cube P8, Half-cube P2, Half-cube P4, or Half-cube P9 (8 cubes of 8 mm, 2 half-cubes of 9.6 mm, 4 half-cubes of 9.6 mm, or 9 half-cubes of 9.6 mm) were put on the tongue of 8 subjects.

Fig. 28 Relationships between log *x*50 and log *N* for four kinds of Optosil cubes: Cube P8, Half-cube P2, Half-cube P4, or Half-cube P9 (eight cubes of 8 mm, two half-cubes of 9.6 mm, four half-cubes of 9.6 mm, or nine half-cubes of 9.6 mm). Data points are means for 8 subjects and SEM; the mean values were curve-fitted using a 2nd order polynomial function. Horizontal hatched lines, log *x*50 levels at the initial larger edge size of the half-cubes (=log 9.6 = 0.98), and at half of the initial size of the half-cubes (=log 4.8 mm = 0.68). Horizontal hatched dotted lines, the same for cubes with an edge size of 8 mm, i.e. levels at log(8mm) and log(4mm). Arrows, the size interval needed to be bridged by food comminution to attain halving of the initial particle size (T. Liu, et al., 2018).

As obviously seen from Fig.24, the observed curves shifted to the left with decreasing the number of cubes (with larger particle size) indicating that the number of chewing cycles required to halve the particle size becomes smaller. This is due to the fact that the particles with larger size has a larger chance of selection. The number of chewing cycles required to halve the initial particle size *N* (*X*0/2) can be determined from the intersection of the experimentally observed curve and the horizontal hatched line at log 4.8 = 0.68; from the left to the right, the values of *N* (*X*0/2) were 3.8 (=100.58), 5.5 (= 100.74) , 12.5 (=101.10) and 15.9 (= 101.25). (Liu, Wang, Chen, & van der Glass, 2018).

At a smaller number of chewing cycles, the double logarithmic plot log *x*50 – log *N* was found convex, but tended to be linear at a larger number of chewing cycles, and its negative slope is *d* as shown in eq. (4). The parameter *d* gives the information about the decrease of the median particle size per chewing stroke (Olthoff et al., 1984).

As for the broadness parameter *b* in eq (1), it was found to decrease with increasing chewing cycles and seemed to level off at 2.2 with increasing *N* (Liu, Wang, Chen, & van der Glass, 2018).

Experimentally determined breakage function is shown in Fig.29.

Fig.29. Cumulative weight fraction undersize *B* as a function of the relative particle size *X* /*X*o for three subjects S15-S, S07-S, S04-S. Drawn lines are best fits through the data points according to eq. (2) using the value of *r* indicated beside each curve. As seen from eq. (2) for breakage function, *B* = 0 and 1 for*X* /*X*o = 0 and 1, respectively (H. Liu et al., 2020)**.**

A similar figure was shown previously in Fig.4 of a paper by van der Bilt et al (1987) for three subjects 1, 3 and 7, where the chewing efficiency of subject 1 was higher than that of subject 7.

The tendency shown in Fig 25 in the present paper coincides with the previous findings. The value of *B*increased with increasing *r* at a fixed value of *X* /*X*o (0 <*X* /*X*o < 1)indicating that the parameter *r* represents the degree of fragmentation.

Experimentally determined selection function is shown in Fig.28.

Fig.30. Selection chance, S, for breakage per chewing cycle as a function of particle size *X* (mm) for

subjects l, 3 and 7 according to equation (1). The solid lines refer to an early phase, 20-25 chewing cycles, and the dashed lines to a late phase of the chewing process, 80-85cycles. For subject 3 both lines coincide so the dashed line is omitted (van der Bilt et al., 1987).

To avoid the overlapping, only typical results for subject 1, 3 and 7 are shown in the above figure. The subject 1 had the poorest chewing efficiency as could be seen for the number of chewing required to halve the particle size from 8 mm to 4mm and with large *r*, and the subject 7 had good chewing efficiency with small number of chewing required to halve the particle size, and poor breakage but large selection *S*. The subject 3 showed the intermediate between 1 and 7.

Recently, it was pointed out that all previous studies did not take into account the anisotropic nature of particles, and that the analysis of particle size distribution can be improved by using the border minimal Feret diameter (Zhang, Jia, Wang, Chen, van der Glas, 2021). These authors excluded the largest and smallest particles to make the estimation of particle size easier. However, these fractions must influence the interaction of particles with saliva, and the grittiness sensation, thus these problems remain in a future study.

**4.1.2 Matrix formulation of breakdown process**

To see systematically the size breakdown process, it is convenient to use a matrix representation. It is necessary to see the transition of the size distribution from *N* chewing cycles to (*N*+1) chewing cycles. The comminution matrix A is written by a selection matrix ***S*** and a breakage matrix ***B*** as follows:

***A*** = ***BS*** + ***I*** – ***S***,

where ***I*** is the unit matrix, the diagonal elements are one, the non-diagonal elements are zero, and thus multiplication of a distribution by matrix ***I*** does not change the distribution (van der Bilt et al., 1987). The term ***BS*** represents the breakage of the selected particles and ***I - S*** represents the portion of feed not selected for breakage.

When the weight fraction on the upper sieve is written *f*1, that of the second sieve *f*2, that of the third sieve *f*3, the column vector ***f*** = (*f*1 *f*2 *f*3)T is ( where the superscript T indicate the transpose operation used for changing the row vector to a column vector) called a feed vector, representing the size distribution after *N* strokes and this size distribution is changed to the column vector ***p*** = (*p*1 *p*2 *p*3)T, called a product vector after (*N*+1) strokes. Then, the transition can be written as

**A*f* = *p***

In the experiments, particles were classified into 10 size classes, but for avoiding the complicated notation, these authors used three or six classes.

The elements of matrix ***B*** can be calculated from the fragmentation value *r* which can be determined from the experiments. Two unknown variables u and w in matrix S can be determined by the least square fitting to minimize the difference between the experimental values and the calculated values. The matrix ***A*** thus determined is for one chewing. Then, after N chewing the product vector p can be written as follows:

**A***N****f***= ***p***

This is the advantage of matrix representation method which gives a clear vision, and this can be used both for theoretical distribution function such as Rosin-Rammler function or experimentally determined distribution (Lucas & Luke, 1983; Lucas, Prinz, Agrawal, and Bruce, 2002; van der Glas, van der Bilt, Olthoff & Bosman, 1987). In the further breakdown process, fragmented particles stick together with the aid of saliva to form a cluster, and also the size of teeth determine the selection function (Lucas, Prinz, Agrawal, and Bruce, 2002; van der Glas, van der Bilt & Bosman, 1992).

The degree of the size reduction was represented by a breakage function. It is a measure of the size distribution of fragments. Lucas et al (2002) showed that the breakage function could be represented as a function of the square root of the ratio of toughness and the Young’s modulus of foods, (R/E)1/2, where R stands for the toughness and E the Young’s modulus. Fig.31 represents the plot of the breakage function vs (R/E)1/2 for 38 different foods, nuts, cheese, raw fruit and vegetables, breads, and others.

Fig.31 The food property group (R/E)0.5 appears to be inversely proportional to the estimated breakage function for 38 foods. Key (foods are unbranded or their variety and origin are unknown unless stated) Nuts: 1 Brazil nut kernels (Eden’s, Australia), 2 hazelnut kernels (Eden’s, Australia), 3 macadamia nut kernels (Eden’s, Australia), 4 cashew kernels, 5 blanched almonds (Eden’s, Australia), 6 roasted salted peanuts (Planter’s, Nabisco, Singapore), 7 pistachios, 8 betel nuts, 9 raw peanuts. Cheeses: 10 Parmesan, 11 white Cheshire, 12 Edam, 13 processed cheese (Apericube, Bel, France), 14 reduced fat cheddar (Mainland, N.Z.), 15 Cracker barrel cheddar (‘Tasty’, Kraft, U.K.), 16 mozzarella, 17 smoked cheddar (King Island, Australia), 18 Double Gloucester, 19 Gouda, 20 Emmental, 21 Lancashire, 22 Leicester, 23 Danish feta, 24 Gruyere, 25 Raclette, 26 Jarlsberg, 27 English mature cheddar. Raw fruit and vegetables: 28 Carrot, 29 green turnip, 30 potato (Russet Burbank), 31 swede, 32 banana. Breads: 33 White bread — dry (Garden, Hong Kong), 34 white bread — soaked in water (Garden, Hong Kong), 35 brown bread — dry (Denny’s, Hong Kong), 36 brown bread — soaked in water (Denny’s, Hong Kong). Miscellaneous: 37 Soyabean curd (Nestlé, Hong Kong), 38 monocrystal sugar (Taikoo, China). (Lucas et al, 2002).

**4.2 Particle size of boluses**

Particle size distribution was thought to be one of the most important criteria to determine the moment of swallowing. Granulometry, study of the determination of size distribution has been done in two different methods, depending when the bolus is collected; the bolus being collected either after a predetermined number of strokes (chewing test, C-test) or at the swallowing threshold, that is, when the bolus is sufficiently cohesive and plastic to trigger swallowing (mastication test or M-test) (Bonnet, Batisse, Peyron, Nicolas, Hennequin, 2019; Gonçalves, Schimmel, van der Bilt, Chen, van der Glas, Kohyama, et al, 2021). Since the goals and methods of C-test and M-test are different, it is necessary to take into account this problem when particle size distributions reported in different papers are compared.

Much efforts have been dedicated to understand the moment at which the bolus is swallowed. Foods must be fragmented to small particles, but as has been clarified by previous studies that the particle or grittiness sensation of fragments depends not only on the particle size but also the shape and hardness because softer particles are thought not to damage the soft tissues of oral organ and larger particles may be acceptable in comparison with harder particles (Chen, Khandelwal, Liu, Funami, 2013; Engelen, et al., 2005; Tyle, 1993). Gritty sensations are generally thought to be a negative attribute for many foods, but this depends on foods and the individual difference in the liking. Some Japanese consumers prefer the red bean paste not completely lost the particle sensation although they like creamy sensation in ice cream or chocolate.

Prinz and Lucas (1995) examined the swallow threshold using four fractions of raw Brazil nut particles with different particles sizes, (i) 5.6-4.0 mm, (ii) 4.0-2.0 mm, (iii) 2.0-1.4mm and (iv) below 1.4mm. They prepared suspensions of these nut particles dispersing in yogurt so that the concentration of particles ranged from zero (no particle) to 100% (nuts particles alone). Number of chews as a function of concentration increased though it was not linear and also showed some scatter. Particles below smaller than 2.0 mm were found to be swallowed but if the concentration was higher than 20%, they required to be comminuted to be lubricated. Since the particle sensation was dependent on not only on the particle size but also on the shape and rigidity of the particle, it is expected to study using different particles. In addition, as discussed earlier, the role of saliva should be taken into account especially for higher concentrations (Nishinari and Fang, 2018; Pangborn and Lundgren, 1977).

Minced foods were expected to help dysphagic patients who have the difficulty in mastication. Yoshimura, Kuwano, Funami & Nishinari (2008) examined the effectiveness of minced foods using minced carrots mixed with thickeners xanthan and gellan gum. They found that the mixed xanthan and guar thickener at the mixing ratio Xanthan : Gellan = 0.2 : 0.4 was found the best for aged panellists because this minced carrot were found the easiest to manipulate for healthy elderly but it was found too sticky for younger healthy panelists. Therefore, it is necessary to take into account the mastication ability when the palatability and easiness of eating were examined.

Particle size distribution has been studied extensively from various points of view: 1) to which size the fragmented foods should be reduced, 2) this is related to the grittiness and creaminess sensation, 3) the release of taste and aroma is enhanced by the increase of total surface area induced by the newly exposed surfaces.

Fragmented food particles were expectorated after fixed number of chewing, and were separated and dried, and then scanned. The particle size distribution was found to be represented well by a stretched exponential distribution function (Kobayashi, Kohyama, & Shiozawa, 2010; Moritaka, Yamanaka, Kobayashi, Ishihara, & Nishinari, 2019). It was reported that not only the molar mass and elastic modulus of gel forming polysaccharides but also the serving size of gels influence the particle size distribution of the bolus (Moritaka et al, 2019).

Effects of the addition of thickeners and small pieces of solid foods to carrot juice on the rheological and sensory properties have been studied recently (Yamaguchi, Torisu, Tada, Tanabe, Kurogi, Mikushi, et al., 2019). Tested samples were: carrot juices containing a commercial thickener with various concentrations without solid foods, mixture of 2 grams of carrot or banana and 3 mL carrot juice. The weight of the spitted out food just before swallowing was found increased for the mixed sample consisting or carrot juice + carrot + banana, which was ascribed to the increase of saliva secretion. Sweetness of banana also might have contributed to the increase of saliva secretion. On the other hand, the weight was decreased for samples with low concentration thickeners, which was interpreted that these samples entered oropharynx earlier by gravity which made it impossible to spit out that part of food. Since it is not possible to eliminate completely a portion which enters oropharynx during the test as suggested by authors and previous researchers, further study is expected to clarify this. The particle homogeneity index (HI), and the particle size index (SI) were found to become higher with increasing the thickness of the test sample. These were interpreted that when a thickener surrounds the food, the food boluses are formed with particles that are bigger and more heterogeneous in size. It was found that the easiness of swallowing of the mixtures of carrot juice and solid carrot increased with increasing concentration of added thickeners, which was thought to be consistent with previously reported results but the results were observed for young healthy persons and so it should be compared with the tests involving elderly persons. For elderly subjects, the time per one chew (chewing time/chewing number) for minced carrot mixed with xanthan (X) and guar gum (G) became shortest for the mixing ratio X:G = 0.2:0.4 at which the viscosity of the mixture became maximum while it was not the case for younger subjects (Yoshimura, Kuwano, Funami, & Nishinari, 2008).

Tribological aspects were found important, and the tribological measurements have revealed the creaminess sensation is closely correlated with friction coefficient and also contributed to the understanding of the swallowing process (Stokes, 2012; Stokes, Boehm, & Baier, 2013). As is well known, the creaminess of ice cream and custard pudding is a key attribute which makes these foods palatable (Civille, 2011).

**4.3 Granulation and bolus formation**

To evaluate the mastication efficiency, gummy jellies and chewing gums have been used as model materials, and their advantages and limitations have been discussed in detail recently (Gonçalves et al., 2021).

Wet granular materials have been attracting much attention because of its ubiquity in various fields and especially has been studied in soil mechanics and industrial products (Luding, 2008; Mitarai & Nori, 2005; Nedderman, 1992). Small granular solid is called a powder, and the boundary between a powder and granular material is conventionally taken as 100 μm (Duran, 2000). It is well known that dry sands cannot pile so high and the angle of repose is ca 35°, but children can build a castle using wet sands. Dry particles agglomerate when some liquid is added, and above a saturated liquid content, they show a slurry-like state (Table 8).

Table 8. Granular media with various amounts of liquid. In the schematic diagrams in the third column, the filled circles represent the grains and the grey regions represent the interstitial liquid (Iveson et al, 2001; Mitarai & Nori, 2006)

Bolus can be schematically represented by a mixture of spherical granules with different sizes (Fig.32a). To understand the structure of the bolus, it is better to begin with the force between two spheres (Fig.32b). Attractive forces between wet granules originate from capillary forces. For two spheres of identical size with radius *R*, the capillary force *F* is given by 2π*Rγ* cos *θ*, where *γ* is the interfacial tension, and *θ* is the contact angle. It was shown that the capillary force between two spheres decays with increasing the separation distance S, and that a capillary bridge ruptures beyond a critical separation distance Sc, and a new capillary bridge can only be formed, if two beads touch each other (Fig.32c) (Scheel, 2009).

Fig.32. a) Schematic representation of a capillary bridge between two beads with separation distance S and a half opening angle β of the capillary bridge. b) The capillary force decays with increased separation distances (Scheel, 2009).

It is well known that cohesiveness of flours increases in the presence of a small amount of water in kneading, but the addition of more water makes it into a slurry. Similar phenomena were observed for oil seed pastes such as peanut or sesame, and was referred to “hard-to-swallow” when the wetting of paste with saliva increases at initial stage before turning into a slurry (Nishinari, Fang, & Rosenthal, 2019; Rosenthal & Yilmaz, 2015).

Ishihara et al (20211) examined the rheological properties of artificially prepared boli by combining compression and rotation of a plunger. Model boli were prepared by subjecting a cylindrically molded gel, 20 mm in diameter and 10 mm in height (approx. 4.5 g) to 10 cycles of vertical compression at 17.8 mm/s with 2.0 mm-clearance and simultaneous rotational shearing by 12 °/s with or without artificial saliva. These instrumentally “masticated” gel boli showed a smaller modulus than a bulk gel, and *G*′ decreased with increasing saliva content. Values of *G*′ for model boluses as a function of frequency were found almost independent of the frequency as is widely found for so-called weak gels (structured fluids with a non-zero yield stress) except the boluses consisting of psyllium seed polysaccharide alone. Fig.33 shows a plateau value of *G*′ at 1 rad/ s as a function of the saliva content. The amount of saliva addition was estimated from previous reports that the rate of stimulated saliva flow is 0.77-4.15 ml/min (Jenkins, 1978) and 1.25 ± 0.67 ml/min (Engelen, Fontijn-Tekamp, & van der Bilt, 2005)

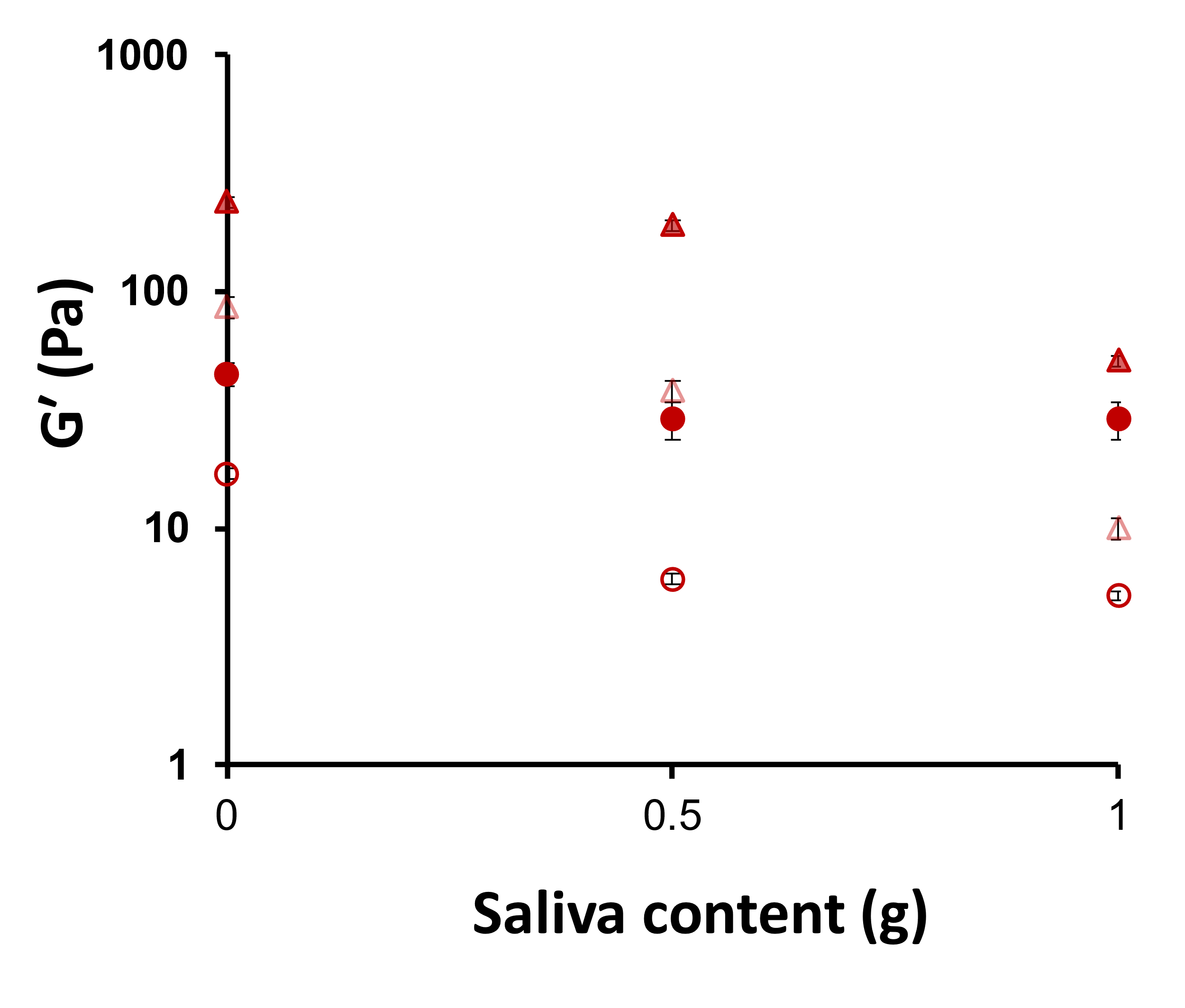


Fig.33 *G*′ for model boli as a function of saliva content. Open circles: 1.0% SAN SUPPORT G-1014 (a mixture of de-acylated gellan gum and psyllium seed gum); Closed circles: 1.5% SAN SUPPORT G-1014; Open triangles: 0.075% KELCOGEL (de-acylated gellan gum); Closed triangles: 0.15% KELCOGEL made from Fig.yy (Ishihara et al, 2011). (at 20 ℃, strain of 1%, angular frequency 1 rad/ s)

The storage modulus *G*′ for boli made from deacylated gellan decreased with increasing content of saliva alone while *G*′ for boli made from a mixture of de-acylated gellan gum and psyllium seed gum decreased by the addition of a small amount of saliva (the addition of 1g saliva corresponds to the saliva volume fraction ca. 0.05) and then tended to level off. This difference might originate from the difference in the miscibility of saliva with crushed gel fragments consisting of deacylated gellan alone or a mixture of deacylated gellan + psyllium seed polysaccharide, leading to the difference in the amount of interstitial liquid shown in grey color in Table 8 or blue color in Fig.30. The effect of the amount of interstitial liquid on the elastic modulus was examined by Møller & Bonn (2007).

Møller & Bonn (2007) found that the normalized storage modulus *G*′ of wet granular materials increased and then decreased as a function of liquid volume fraction．Their samples were 100 µm polystyrene beads and silicone oil (1), 100 µm glass beads and water (2), 100 µm glass beads and silicone oil (3), 100 µm sand and water (4), 25 µm glass beads and silicone oil (5), 3 µm PMMA beads and silicone oil (6) and all of these samples showed the same dependence on the liquid volume fraction. These authors showed that *G*′ of these wet granular materials increased with increasing Young’s modulus *E* of the beads and also with increasing the surface tension γ of the liquid, and thus *G*′ / *E*2/3 *γ*1/3 decreases with increasing bead radius based on scaling concept. Similar results were reported for glass beads and basalt beads with the radius 68 µm in the presence of liquid (water) (Scheel, 2009).

Although the quantitative estimation of Young’s modulus *E* of masticated food particles and the surface tension of liquid consisting saliva and exuded liquid from food may be difficult without causing damage of food particles, in addition, the particle size distribution in the food bolus may be far from monodisperse, the estimation used for plastic or mineral monodisperse particles will confer the basis of the estimation of the order of the magnitude of food bolus rheology.

Fig. 34. Master curve of G′ for several materials (100 µm polystyrene beads and silicone oil (1), 100 µm glass beads and water (2), 100 µm glass beads and silicone oil (3), 100 µm sand and water (4), 25 µm glass beads and silicone oil (5), 3 µm PMMA beads and silicone oil (6)). The curves for the different materials have been rescaled using: G′ → G′ /(0.054 *R*−1/3*E*2/3*γ*1/3), where *R* is the bead radius, *E* Young’s modulus of the beads material and *γ* the surface tension of the fluid (Møller & Bonn, 2007).

It should be noted thatFig. 34 cannot be directly correlated in the oral processing because particles used are rigid and the size was kept constant and only the liquid content was changed. In FOP, the solid food is comminuted into smaller particles, and then agglomerated into larger granules forming a cohesive bolus (Boehm, Yakubov, & Stokes, 2020).

After the breakdown process of solid foods by first bite followed by comminution (chewing), food particles are agglomerated in the presence of saliva. The agglomeration process of particles has been studied in detail in powder technology and is called “granulation”. Granulation is defined in the powder technology as the process of agglomerating particles together into larger, semipermanent aggregates by spraying a liquid binder onto the particles as they are agitated in a tumbling drum, fluidized bed, high shear mixer, or similar device (Iveson and Lister, 1998; Ennis and Litster, 1997). The liquid binds the particles together by a combination of capillary pressure, surface tension, and viscous forces. In food oral processing, instead of spraying a liquid binder, secreted saliva plays a role of binder, and instead of a tumbling drum, fluidized bed, high shear mixer, or similar device used in chemical engineering powder industry, the transport of the agglomerated particles (that is granules in the powder technology), called bolus in FOP is carried out mainly by tongue-palate-cheek in the presence of saliva.

The granulation, the agglomeration process of solid particles in the presence of liquid binder (saliva in FOP) may be classified into two types as shown in Fig. 35.

Fig. 35 The initial stage of the agglomeration process in the presence of liquid binders. High deformation systems for soft and deformable particles (left) and low deformation systems for hard particles (Iveson et al., 2001)

When the particles are soft and deformable, they form large areas of contact during collision, leading easily to the coalescence, and thus the liquid binder content increase the rate of growth (left of the Fig. 35). On the other hand, when the particles are hard and cannot deform to coalesce during impact, the coalescence of particles will be delayed after squeezing liquid binders to their surfaces. Then, the coalescence proceeds rapidly resulting in the growth of size (right of the Fig. 35). In the chemical engineering of powder production, only nucleation occurs without growth of size when the binder is insufficient, and oppositely overwetting occurs when too much liquid binder is added. When the formed granules are too weak and form a loose crumb material, they cushion a few larger granules which are constantly breaking and reforming. Therefore, it is necessary to take into account the dynamic equilibrium between coalescence and breakage. Iveson et al. (1998, 2001) further analyzed this process hypothesizing the granule growth behavior is a function of only the pore liquid saturation and the amount of granule deformation during compact.

Fluid gels (microgels) have been produced and utilized to modify the food texture as mentioned before. Recently, it was used as thickening agents for dysphagic treatment (Zhang et al, 2023). Microgels with different sizes mixed with artificial saliva might be used as a model bolus to study the rheological properties of bolus systematically. Dual behaviour of microgels as granular matter and colloidal glass was studied recently (D’Oria, Gunes, Lequeux, Hartmann, Limbach, Ahrnea, 2023). D’Oria, et al (2023) found that microgels form a granular pile when microgel particles sediment, angling like a sand pile of a conical shape, which is a signature of granular materials (Beakawi Al-Hashemi & Baghabra Al-Amoudi, 2018). In addition, these microgels were found unable to reach a thermodynamic equilibrium at the level of the particle motion within the suspension, i.e., characterised by slow dynamics which was a signature for colloidal glass (D’Oria, et al , 2023).

Further analysis of food bolus formation based on the developments in powder and granular technology taking into account the surface tension, viscosity, density of saliva will be useful to advance the understanding of food oral processing.

**4.4 Swallowing**

The moment of swallowing depends on two major factors: the food textural and physical properties (i.e. hardness, stickiness, cohesiveness, moisture content, portion size) and oral as well as general physiological characteristics of an individual (i.e. dentition, biting/chewing force, tongue motility, salivary flow rate, age, neurological status, pain, intra-oral sensitivity) (Gonçalves et al., 2021; Gray-Stuart, Jones, & Bronlund, 2017; Peyron, Gierczynski, Hartmann, et al, 2011; Sato, Ono, Kon, et al., 2016; Schimmel, Voegeli, Duvernay, Leemann, & Muller, 2017; Shiozawa, Kohyama, &Yanagisawa, 2014).

Prinz and Lucas (1997) and Lucas et al (2002) proposed a model to analyze the swallowing process of bolus. In this model, particles constituting bolus adheres to the oral lining due to a primary attraction through surface tension. The adhesive force *F*A is given by *F*A = 4π*r*γ, where *r* is the radius of the spherical food particle and γ is the surface tension of the oral fluid (Fig. 36a). Assuming that the particles are packed into a ball, the maximum force, *F*V, holding them together can be estimated by taking a central section between two disc-like surfaces (Fig. 36b). The viscous force required to separate these discs is *F*V = 3π*ηD4/*64*d2t,* where *η* is the viscosity of the oral fluid filling spaces between the food particles, *D* is the radius of the disc, *t* is the time span over which the separation takes place and *d* is the average distance between particles.

Fig. 36. (a) The geometry assumed for a surface tensional force, *F*A, which could attract a spherical food particle to the relatively flat lining of the oral cavity. This force depends on particle size but is independent of the distance between the particle and lining. (b) An idealized ball of spherical food particles, after being packed by the tongue against the hard palate, with the spaces between particles being filled by saliva. There is a highly distant-dependent viscous force that tends to hold the particles together to form a bolus (Lucas et al, 2002).

The force that tends to stick food particles together is *F*V, while that which would attract them to the oral cavity is *F*A. Then, particles will agglomerate, and bolus formation should begin when the cohesive force *F*C = *F*V - *F*A> 0 and swallowing will take place when particles cohere most strongly, in other words, *F*V - *F*A is maximized at the moment. Prinz and Lucas (1997) selected Brazil nuts and raw carrot because these foods do not exude liquid so much on biting, and the oral fluid mentioned above can be assumes as saliva. Then, the cohesive force *F*V - *F*A as a function of the number of chews was calculated by computer simulation as shown in Fig.35.

Fig. 37 The cohesive force, *F*V - *F*A, is plotted against the number of chews taken in the masticatory sequence for raw carrot (circles) and Brazil nut (squares). A trend line is plotted because of great variability deriving from repeated runs of the packing simulation to find inter-particle distances. The force is initially negative, resulting from the predicted propensity of larger particles to stick to the mucosa lining the oral cavity. As saliva is secreted and particles get smaller, particles start to stick them together. The predicted force is in the low mN range. The cohesive force seems to peak between 15–25 chews (in rough accordance with published data — Lucas & Luke, 1986), and declines thereafter as excess saliva floods the bolus, so separating particles (Lucas et al., 2002).

In the development of detailed mechanism of mastication and the subsequent swallow using raw carrot and Brazil nuts, Prinz and Lucas (1997) proposed that after the formation of lubricated bolus made from the fragmented particles mixed with saliva, the swallowing occurs at the moment when the cohesiveness became maximum because after that moment the overwetting causes the particle separation. However, it is intuitively difficult to justify this hypothesis because higher cohesiveness may mean a higher viscosity or longer residence time in the mouth. Chen and Lolivret (2011) examining the eating difficulty found that the longer residence time was correlated well with the eating difficulty, and they further found a good correlation of the viscosity and especially stretch-ability with the longer residence time, i. e., the difficulty in swallowing. Since the stretch-ability can be quantified by the fluid extension measurement, which gives a good measure for cohesiveness, the concept of cohesiveness was revisited (Nishinari, Turcanu, Nakauma and Fang, 2019). These authors pointed out that an erroneous usage of this concept of cohesiveness in the dysphagic treatment should be rectified, and showed an evident example showing that the cohesiveness of xanthan solution decreased with increasing xanthan concentration if adopting such an erroneous definition and measurement (Nishinari et al., 2013). As discussed earlier in relation with safety, the method of measurement of cohesiveness for solid and liquid is different. Therefore, the determination of the time at which the cohesiveness becomes maximum is not simple.

It was suggested that a coherent bolus is safer to be swallowed because it does not scatter into smaller fragments (Nakauma, Ishihara, Funami, & Nishinari, 2011; Nishinari, Turcanu, Nakauma and Fang, 2019; Tobin, Mihnea, Hildenbrand, Miljkovic, Garrido-Bañuelos, Xanthakis, et al., 2020).

**The results reported by Prinz ad Lucas shown in Fig.30 was interpreted that the swallowing occurs when cohesive force becomes maximum when food particles were bound together. Further chewing will separate agglomerated particles by incorporating excessive saliva, and thus the bolus should be swallowed at the moment when the cohesive force becomes maximum (Boehm et al, 2020; Panda et al, 2020).**

**In parlance of granular matter, the time at which the cohesiveness becomes maximum as shown in Fig.37** (Lucas et al., 2002) corresponds to the peak shown in Fig.34 (Møller & Bonn, 2007). Four phases of wet granular materials in Table 8, pendular, funicular, capillary and slurry with increasing liquid content (saliva and liquid exuded from food) could be found to correspond to temporal phases of ingested food in the oral cavity.

**Instrumental simulation of swallowing**

Enormous efforts have been made to ensure the safe ingestion of foods especially to avoid the aspiration (Cichero, Lam, Chen, Dantas, Duivestein, Hanson, et al., 2020; Marconati, Engmann, Burbidge, Mathieu, Souchon, Ramaioli, 2019; Methacanon, Gamonpilas, Kongjaroen, Buathongjan, 2021; Nishinari, Takemasa, Brenner, Su, Fang, Hirashima, et al. 2016). Although Texture Profile Analysis (TPA) is useful for most solid foods, the misuse of TPA parameters for liquid foods has led to misunderstandings and confusion (Nishinari, Kohyama, Kumagai, Funami and Bourne, 2013). Numerical calculation to simulate the swallowing has been employed by some research groups (Sonomura, Mizunuma, Numamori, Michiwaki, & Nishinari, 2011).

A simple model mimicking the swallow has been proposed (Mackley, Tock, Anthony, Butler, Chapman, & Vadillo, 2013), and has been used by some research groups (Lavoisier, Shreeram, Jedwab, & Ramaioli, 2021; Patel, Scott, Patel, Mohylyuk, McAuley, & Liu, 2020).

1. **Individual difference in oral processing**

It is necessary to take into account the individual difference which influences the oral processing. Each person has his/her own habitual or preferred way of mastication conditioned by his/her lips, tongue, teeth, cheeks, and palate. Gender differences in the movement velocity during mastication were found (Shiga, Kobayashi, Katsuyama, Yokoyama, & Arakawa, 2012). According to an internal report summarized by Engelen and de Wijk (2012), grouping of mastication behavior was proposed based on an introspective interview of subjects who were asked to describe what they did after placing the food in the mouth. Two semi-solid foods, custard and mayonnaise were chosen, and the subjects were classified into four group, “simple” (50%), “taster” (20%), “manipulator” (17%) and “tonguer” (13%). “Simple” subjects placed the food on the front of the tongue, raised its tip to the palate to form a seal with the sides of the tongue against the teeth, then retracted the tongue and swallowed the food. “Tasters” first moved the food backward in the simple manner described above, but additionally made a series of short sucking movements against the palate before swallowing. “Manipulators” described a wide variety of behaviors, sometimes chewing with the incisors and allowing the food to flow into the buccal sulcus and/or chewing between the molars. “Tonguers” made back and forth and sideways movements of the tongue against the palate (Engelen and de Wijk, 2012). Even for these two semi-solid foods, these authors found that subjects use their own way very different each other.

The different oral processing ways must be due to the different physiological structure of teeth, tongue, cheeks, saliva flow rate etc, and it also depends on food characteristics as had been discussed (Hiiemae, 2004; Peyron, et al., 1996, 1997; van der Bilt, 2011, 2012).

Jeltema, Beckley and Vahalik (2015, 2016) classified mouth behavior into four groups : crunchers, chewers, suckers and smooshers. Crunchers like foods such as crispy apples, vegetables, cookies that they can crunch; chewers like foods such as chocolate covered raisin, strawberry, chewy candies, brownies, sausages and cheese chunks that they can chew; suckers like foods such as hard candies, caramels, chocolates that they can suck for a long time and often suck on them until they dissolve; and smooshers like foods such as custard, cottage cheese, soft serve ice cream, ripe banana that they can smoosh. These four groups each show their favorite mouth processing way which makes them choose suitable foods. The difference in liking was divided into two, “love” and “not worth to buy” based solely on texture. These authors found that each group like foods which are typically preferred in each group. It seems a little bit tautological. Actually, they also stated that “much needs to be understood about the role of physiological differences and their relationship to Mouth Behavior (MB), to include: salivary flow, mouth size, dental bite, dental condition (braces, etc.) and dental health”. This was also pointed out by Engelen and de Wijk (2012): each consumers have their own anatomical difference in using lips, teeth, cheeks, tongue and palates to process food in the mouth leading to different preferred mouth behavior.

More recently, Wilson et al (2018) re-examined whether eating mouth behavior can be grouped or not using four different foods with a wide range of texture, Walkers Shortbread, Twix [shortbread cookie with a layer of soft caramel and coated with milk chocolate], Cheetos Puffs [extruded cheese snack], Mentos Mint [hard shell with soft chewable inside piece candy]. These are the same foods used by Jeltema et al. (2016) in investigating their MB hypotheses. Using a video jaw tracking, they obtained 28 chewing parameters both temporal and spatial, including the closing and opening period, length of chewing sequence. One hundred subjects (69 female and 31 male) participated the test. However, the individual chewing parameters did not give a clear separation between four groups crunchers, chewers, suckers and smooshers. Then, choosing 19 variables and using a discriminant analysis, they got a 68% correct classification according to the mouth behavior grouping.

More recently, Jeltema et al. (2020) modified their MB model introducing the evaluation of temporal aspect. They instructed subject to write the temporal change of the texture at the beginning, early middle, late middle and the end before swallowing. This is similar to TDS but there may be more time for subjects to write the texture terms from the list and if not found subjects write the term by themselves. They found again the each group Crunchers, Chewers, Smooshers, and Suckers liked a food if they could manipulate that food in the mouth in their favorite way. According to their hypothesis, Smooshers would try to make “smooshy” a food they found “chewy” or “hard”, and therefore their ability or inability to adapt their mastication strategy would determine their liking or disliking of that food. However, some Smooshers may be able to change their strategy without so much difficulty, and in such a case, the above-mentioned speculation may not be valid. The validity of the grouping into their four groups, Crunchers, Chewers, Smooshers, and Suckers should be reconsidered, and each member classified as one of four groups may have the freedom of choice and may change his/her strategy during the oral processing. It is evident that a human fractures a crispy food, and then fragmented pieces will absorb saliva, and thus lubricated to be formed into a bolus and then swallowed. This is not limited to a person affiliating to a group “cruncher” but also other persons affiliating to other categories “chewer”, “sucker” or “smoosher”.

It is expected that how the different groups of eating behavior, mouth behavior, is related with physiological oral condition is clarified. Kim and Vickers (2020) re-examined the validity of Jeltema’s grouping relating consumers’ liking with Mouth Behavior. They performed online survey on food texture liking asking 288 participants to rate the liking of 106 texture attributes. Since the Jeltema/Beckley Mouth Behavior (JBMB) classification tool, which provides pictures of specific foods that illustrate their summary statements (i.e., “I like foods that I can crunch,” “I like foods that I can chew,” “I like foods that I can smoosh; I even smoosh foods that I can chew,” and “I like foods that I can suck on a long time, and I often suck on them until they dissolve”), cannot cover other foods which are not included in the illustration, and thus may miss the broader textural attributes, Kim and Vickers (2020) used 106 attributes expecting that liking responses would have more broadly reflected a greater scope of foods. Among these attributes, creamy, crips and juicy were found most “like” and slimy, plastic, sandy most “dislike”. In addition, five terms, ductile, cellular, short, glutinous, and friable were not familiar for participants, and these five were removed from the further survey. It was found that percentages of Chewers, Crunchers were higher, and those of Smooshers and Suckers were lower than in the previous result of Jeltema et al. (2015). This was ascribed to the difference in the age of participants; while the age of participants ranged from 15 to 65 in Jeltema’s work, there were no participants under the age 18 in Kim and Vickers’ work. Kim and Vickers expected that most of the attributes were related to the oral physiological parameters based on what is known about their roles in food oral processing (e.g., greater liking for hard by individuals with higher biting forces, less liking for tender by individuals with higher chewing efficiencies, and less liking for rough by individuals with higher particle sensitivities), but this was found not to be the case, and no relations were found. As Szczesniak (1972) noticed, physiological limitations may shape food texture liking in children, but these limitations would apply far less to participants of Kim and Vickers’ work because they were all adults. Then, Kim and Vickers suggested that reasons for food texture liking are primarily learned rather than innate and much more related to specific textures in specific foods. Clustering of participants on their oral physiological measurements in Kim and Vickers’ work gave rise to four clusters: a “low particle-size sensitivity” cluster, a “high biting force” cluster, a “high saliva flow rate” cluster, and a “low saliva flow and low chewing efficiency” cluster. However, although the higher biting force cluster should belong to the Crunchers of Jeltema’s grouping, the percentage of Crunchers turned out to be too low than expected (Table 6 in Kim and Vickers, 2020). Thus, Kim and Vickers (2020) were unable to predict membership in the four mouth-behavior groups from either their texture liking or their oral physiological measurements, and they refuted the idea that large texture-liking subgroups exist.

1. **Texture perception in liquids and solids**

Texture was found more important in semi-slid or solid foods than in liquid foods from a perusal of Hutching-Lillford diagram (Cardello, 1996; Matsumoto and Matsumoto (1977); Nishinari, Hayakawa, Xia, Huang, Meullenet, & Sieffermann, 2008). Although the distinction between liquid, semi-solid and solid foods is sometimes delicate (Nishinari, 2021a, b), it can be interpreted as follows (Engelen and de Wijk, 2012; Nishinari, 2004; Nishinari and Fang, 2018):

1) it takes a longer time for solid foods to be broken down and mixed with saliva during mastication before deglutition, and thus the change in structure or mechanical properties during oral processing is much larger for solid foods than for liquid foods. Due to the longer oral residence time, humans have more time to sense the different textural aspects of semi-solid or solid foods (Engelen and de Wijk, 2012). Beverages are usually drunk in a shorter time except in wine tasting when evaluating the quality of wine.

2) It has been known that Weber-Fechner law, *P =k I n*, holds between the perceived value *P* and the instrumentally measured value *I,* and *n* is the exponent. This exponent was found larger in the elasticity than in the viscosity, indicating that humans are more sensitive in the elasticity change than in the viscosity change (Stevens and Guirao, 1964).

**6.1 Perception and measurement in liquids**

Stevens and Guirao (1964) determined the perceived viscosity of silicone liquids by three nonoral methods: 1) shaking the container, 2) stir the liquid with a rod by blindfolded observers, 3) stir the liquid with a rod by observers who were watching. The instrumental viscosity of the silicone liquids was determined by Brookfield Engineering laboratories ranging from 10.3 mPa.s to 9000 mPa.s, and the exponent was found 0.42 ~ 0.46 (Stevens and Guirao, 1964). Christensen (1979) using three solutions of carboxymethylcellulose (CMC) with different molar masses obtained the exponent 0.29 between the perceived oral viscosity and instrumentally measured viscosity, which was much smaller than the value 0.42 ~ 0.46 obtained by nonoral methods used by Stevens and Guirao (1964).

Christensen noticed that the standard deviation for judgments at each viscosity level was higher for thin solutions of low viscosity, which might affect the exponent value. She also pointed out that shear rate in the oral cavity at which each subject judges the viscosity may have a wider range (Christensen, 1979, 2018). Christensen and Caper (1987) using alginate solutions with different viscosities ranging from 3 mPa.s to 2187 mPa.s (determined by a Wells-Brookfield micro viscometer, Model RVT at 10~300 s-1), instructed subjects to do the following tasks: oral task (swishing the solutions in the mouth), rod task (stirring solutions with a glass rod by a blindfolded subject), visual task (observation of the movement of the solution in a glass tube when tilting), and also stirring the solution by their index finger and then rub the solution between their thumb and index finger by blindfolded subjects). They obtained the exponent 0.34 (oral), 0.35 (rod), and 0.39 (visual).

Kadohisa, Rolls and Verhagen (2005) using water (1mPas) and four CMC solutions with the viscosity 10, 100, 1000 and 10000 mPas obtained the relation between the perceived thickness *T* and the instrumental viscosity *η*. Subjective evaluation of thickness was performed by 12 untrained subjects. The double logarithmic plot of *T* and *η* including five experimental points gave a straight line with a slope of 0.28, which is in good agreement with the result of Christensen (1979).

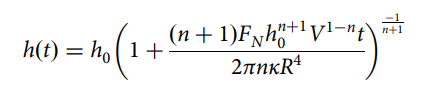
Cutler, Morris and Taylor (1983) reported a good correlation between the perceived thickness *T* and the instrumentally measured viscosity at 10 s-1 for Newtonian liquids, sugar syrups, and the exponent was found 0.22. They noticed that this high correlation between *T* and the instrumental viscosity *η* was not observed for the non-Newtonian liquid xanthan solution. Xanthan solution is known as a structured fluid although it had been erroneously called a weak gel (Nishinari, 2009; Picout and Ross-Murphy, 2003). Xanthan solutions showed a deviation in the double logarithmic plot of *T* and the instrumental viscosity *η*. The same group of Morris later found that a good correlation between *T* and the instrumental complex viscosity *η\** at 50 rad/s, instead of the steady shear viscosity at 10 s-1, for all the polysaccharide thickening agent dispersions of xanthan, guar gum, starch dispersions with varying viscosities (Richardson, Morris, Ross-Murphy, Taylor, and Dea, 1989). The perceived thickness of the 27 samples was assessed by a trained sensory panel to relate each sample to an arbitrary standard (1.25% guar) assigned a value of 100. Thus, in their assessment, a sample assessed twice as 'thick' as the standard was given a thickness score of 200, and one perceived half as thick was assigned a score of 50. They found the value of exponent 0.54. They attributed that reason why the small deformation rheology such as complex viscosity led to a better correlation between *T* and the instrumental viscosity to the possible mechanism that *T* was perceived for the intact network structure of xanthan rather than isolated molecular chains released after rupture of the network by shear (Richardson et al., 1989). Another possibility that panellists evaluated *T* within a small deformation not swallowing down so fast at the initial stage just after the liquid was ingested. The reason however was not yet clarified since the research group left it open for debate. The comparatively high value of exponent 0.54 could be attributed to a temporary network structure formed in xanthan solution which might be perceived somewhat solid-like at lower shear rate, and thus the exponent in the power law relation between the perceived intensity and the instrumentally measured quantity, *P =k I n*, may tend to closer to the value for solid foods, as will be shown below. Time intensity evaluation of xanthan solution was not reported, the viscosity sensation just after ingestion of the sample into the mouth, then swirling the sample solution by the tongue, and then the sensation at swallowing and that after swallowing, should be evaluated by trained panel. Since the instrumental viscosity of the solution depends on the rheological properties, Newtonian, shear thickening or shear thinning, the perceived viscosity may also depend on the shear rate in the oral cavity which changes temporally.

The experimental findings that the exponent in *P =k I n* is lower for viscosity vs perceived thickness in liquid foods is much lower than that for elastic modulus or fracture stress vs perceived hardness or firmness in solid foods may be consistent with the relative insensitivity of palatal pressure induced by viscosity change. Three pressure transducers were installed in the anterior, central, and lateral posterior areas to measure the palatal and the swallowing pressure (Takahashi and Nakazawa,1991a). Takahashi and Nakazawa (1991b) found that the palatal pressure only doubled from 100 dyn/cm2 to 200 dyn/cm2 when the viscosity of orange juice thickened by carboxymethyl cellulose increased three orders of magnitude from 10-2 Pas to 101 Pas. Although these authors did not report the results on sensorily measured thickness of liquid foods, the reported insensitivity of palatal pressure change induced by instrumental viscosity change may explain partially the above-mentioned low values of the exponent. Takahashi and Nakazawa (1991b) noticed that subjects swallowed orange juices thickened by CMC in a single deglutition when the viscosity is low, but thicker juices were swallowed in several smaller portions, which made a simple comparison difficult.

Takahashi and Nakazawa (1992) also examined the palatal pressure change for agar gels and gelatin gels with different rupture stresses. It is known that humans select the squeezing/compression between the tongue and the hard palate for the first breakdown strategy for very soft gels (Arai and Yamada, 1993). It could be seen from their experimental results that subjects selected this strategy when the rupture stress is below 7 ×104 Pa and the palatal pressure increased with increasing rupture stress. However, for hard gels with the rupture stress higher than that value, the palatal pressure was found to decrease indicating that subjects transferred gels to the teeth to be broken. This oral processing behavior was analyzed in more detail using artificial tongue (Ishihara et al., 2013, 2014; Nishinari, Ishihara, Hori, and Fang, 2020).

The relation between the perceived thickness *Th* and the instrumentally measured viscosity *η*N has been studied extensively. For various Newtonian liquids such as syrup, honey and guar gum solutions, a linear relation between log *Th* and log *η*N was found while that relation for “weak gels” (fluids with yield stress. The name “weak gels” was retracted later by one of namers) such as tomato ketchup and xanthan dispersions deviated from the linear relation and the perceived thickness *Th* was found lower than that for the other Newtonian fluids (Morris, 1994). Morris found a high correlation between *Th* and complex viscosity *η*\* at 50 rad s-1 and interpreted this result as *Th* was closely related with unbroken network characterized by *η*\* rather than *η*N where the network was destroyed in making the measurement. On the other hand, the possibility that sensory panellists may not swallow immediately when asked to evaluate the thickness as in the situation of wine tasting. In such a situation, the fluid may stay quiescently before being swallowed, and thus Th would be perceived at low strains.

Recently, another method of analysis using a model that *Th* was proportional to the shear stress σ perceived at the surface of the tongue when the fluid was squeezed between the tongue and the palate during the transportation process of the ingested fluid to the posterior part of the mouth (Deblais, Hollander, Boucon, Blok, Veltkamp, Voudouris, et al., 2021). Deblais et al. (2021) analysed the flow of power law fluids between two rigid plates representing the tongue surface and the hard palate assuming that fluid is a power law fluid with the consistency parameter κ and the power law index *n*. When the bottom plate (tongue) moves at a speed *V* relative to the top (palate) to deform the trapped liquid, the shear stress σ is given by



,

where *h*0 is the initial gap between the tongue and the upper part of the oral cavity, *R* is the radius covered by the liquid product on the tongue, *F*N is the lingual force, and *t* is the characteristic time needed for assessment (i.e. the residence time for the liquid product during the sensory test). Deblais et al. (2021) examined whether the relation between thethickness *Th* and stress σ follower law the power law proposed by Stevens; *Th* ＝*A σ*b or the logarithmic dependence of Weber-Fechner；*Th* ＝*A* log(*σ*）. Fluids used were bouillon soup with various concentrations with negligible yield stress. Including previous data by Blok, Bolhuis, Arnaudov, Velikov, & Stieger (2021), Deblais et al (2021) found that the relation between *Th* and σ was described well by Weber-Fechner for these power law fluids.

Fig.38 Relation between “subjective thickness” and stress σ on the tongue as calculated from Deblais et al, 2021. The black continuous line indicates a logarithmic dependence (Weber-Fechner’s law), while the black dotted line shows a power law-dependence (Steven’s law) (Deblais et al, 2021). These authors stated that further study is needed to take into account the presence of the yield stress when the above analysis is extended to more complex fluids.

* 1. **Texture perception in solids**

As for the relation between the perceived hardness and the instrumentally measured hardness of solids, Harper and Stevens (1964) examined the relation between the instrumental value and sensory hardness using solid samples with varying hardness, sponge rubber to vulcanized rubber. Sensory evaluation was done by 47 subjects who were instructed to squeeze rubber-like samples between finger and thumb, and report the hardness in numbers to indicate how many times or what fraction the various specimens stand in relation to one another. The exponent was found to range from 0.6 to 0.8.

Halmos (2000) examined the relation between the sensory evaluation and instrumentally observed value of hardness using six cheeses with varying hardness. The exponent obtained from the double logarithmic plot of the instrumental reading of hardness (fracture stress) and the hardness sensory score was about 0.77.

Goh, Charalambides, and Williams (2003) examined the relation between the perceived firmness ad the instrumental fracture stress. The sensory evaluation was conducted both by hand and oral evaluation. The exponent from the double logarithmic plot was about 0.74 in oral evaluation and 0.49 in hand evaluation.

Peyron, Lassauzay, and Woda (2002) studied the effects of hardness on the mastication behavior using four different gelatin jellies with compression hardness, which was determined from the maximum stress at the first 50% compression, and varied from 39 to 114 kPa. They observed a power law relation between sensory hardness (SH) and instrumentally observed hardness, and the exponent was reported as 1.69.

To see whether the exponent observed for cheeses by Halmos (2000) and Goh et al (2003) was much smaller than that observed by Peyron et al (2002) was due to the difference of the hardness or firmness determination based on the fracture stress or the stress at the first 50% compression or not, the data of Goh et al based on the Young’s modulus was also examined. The double logarithmic plot of the oral sensory score and the instrumental Young’s modulus was found to be about 0.63. Therefore, the difference between exponent values reported by Halmos (2000) and Goh et al (2003) and the Peyron et al (2002) should be attributed to the difference in Cheese and gelatin jellies. Mechanical properties of both cheeses and gelatin jellies are temperature sensitive, but for the moment, the cause of this difference is not clear, and should be clarified in the future.

Although the exponent in the power law representation between the perceived value *P* and the instrumentally observed value *I* seem to depend on the samples used or the method of the sensory evaluation, the sensitivity of humans is higher for the change in the fracture stress or elastic modulus than in viscosity when all the data mentioned above are taken into account.

Miele, DiMonaco, Dell’Amura, Rega, Picone, Cavella (2017) studied the effects of different sweeteners (sucrose, aspartame, saccharin, MNEI (single derivative chains of monellin) and super sweet Y65R mutant on the mechanical properties of agar gels with different concentrations (1.0. 1.5, and 2.0%). These authors performed the sensory evaluation of hardness by compression between thumb and forefinger. The power law exponent *n* in the sensory hardness SH vs fracture stress FS (SH ~ FS*n*) was found 1.15.

**6.3. Chewing velocity decreases with increasing firmness of foods ?**

This was discussed previously (Nishinari & Fang, 2018). While the chewing velocity for four cheeses with different firmness was found to decrease with increasing Young’s modulus (Dan & Kohyama, 2007), that for gummy jellies with different hardness was found to increase with increasing hardness which was determined from the maximum force in the compressive force-deformation curve (Komino & Shiga, 2017). Takeshita & Nakazawa (2007) found that the chewing speed of different foods with different Young’s moduli decreased with increasing Young’s modulus, which is consistent with the experimental findings of Dan and Kohyama (2007). However, they did not find a good correlation between the chewing speed and the hardness determined from the maximum breaking force. From this finding, they suggested that the chewing behavior of humans is determined by the initial instant of biting a food and not by the force to cut it off by teeth.

Bourne (2002, p.48) stated that first few chews are frequently slower than the regular chewing rate and that tough foods are masticated more slowly than tender foods, which is in line with the above two groups of Nakazawa and Kohyama.

Chewing rate and muscular work during mastication were examined for five foods, melba toast (round disc 2mm thick), breakfast cake, raw carrot, peanut (16 whole peanuts), Gouda cheese with a chewing gum as a reference food (van der Bilt and Abbink, 2017). They hypothesized that chewing rate would be slower for harder foods, but this hypothesis was rejected after the study. They found that the chewing rate changed during mastication, and thus mastication process was divided into five phases. Cycle durations were found to decrease between the beginning phase and the 25% phase with all five foods, and then increased. The number of chewing cycles was smaller for softer foods. Muscular work decreased during chewing for carrot, cheese and cake, but peanuts and melba toast increased during the beginning to the second phase. The difference in muscular work was most pronounced at the beginning, but decreased gradually during chewing as had been reported (Kohyama and Mioche, 2004; Lassauzay et al, 2000). It was confirmed that the harder foods needed a longer chewing time, and especially near the end of chewing before swallowing, harder foods needed more chewing than softer foods.

Fig. 39 Duration of a chewing cycle (average and standard error of the mean; 84 participants) in 5 phases of the chewing process (beginning, 25%, 50%, 75% and end) for five natural foods and for chewing gum. Data points along a line represent the 5 phases of chewing for a food. The lines are for visual aid only (van der Bilt & Abbink, 2017).

Most dental scientists found a similar tendency to that found by Komino & Shiga (2017) which at first sight contradictory to the above mentioned tendency. Anderson, Throckmorton, Buschang, and Hayasaki (2002), Takada, Miyawaki, and Tatsuta (1994), Peyron, Lassauzay, and Woda (2002) also reported that the chewing speed increased with increasing hardness determined as the maximum force at the breaking point in the force-deformation curve. What is the difference between the Young’s modulus and the fracture force? When the Young’s modulus and the breaking force are compared for agar gels and gelatin gels, it was found that the Young’s modulus of a 4.4 wt% agar gel was found larger than that of 25 wt% gelatin gels (Nishinari et al., 1980). In addition, it was found that the different force-deformation curves for gelatin gels, which were grouped into two; one with a higher Young’s modulus but a lower breaking force, and the other with a lower Young’s modulus but a higher breaking force. Therefore, if gummi jellies prepared from mainly gelatin show a similar behavior, i.e. gummi jellies with higher breaking force show lower Young’s modulus, the findings of dental research group are not contradictory with those reported by food scientists (Dan & Kohyama, 2007; Takeshita & Nakazawa, 2007). This situation has been often found in food texture studies. For example, a fresh carrot showed a higher Young’s modulus than a carrot stored one week in a refrigerator although the peak stress in the tress strain curves showed almost the same value for both the fresh and the stored carrots (Thiel and Donald, 1998).

We must also pay more attention to the determination of mastication velocity. While this velocity is determined quite often from the jaw closing velocity by detecting the motion of the canine, Takeshita & Nakazawa (2007) stated that this velocity should be determined from the motion of the first molar because they noticed that the subjects transferred the ingested food to the position of the first molar before the commencement of the biting. Bourne (2002, p.48) stated that the mandible movement is not along the straight line but in the arc-like of a circle around the temporomandibular joint, and that the moving velocity at the incisor is much faster than at the molar. In addition, the applied force on teeth was reported different on three teeth, first bicuspid, second biscupid, and first molar which depended on mechanical properties of foods (Yurkstas and Curby, 1953; Bourne, p.52).

Dental scientists frequently use gummy jellies to know the mastication performance of denture wearers. Kapur, Soman, and Yurkstas (1964) pointed out that the breakdown process of ingested foods in denture wearers was different from that in humans with natural teeth where the coarser food particles were preferentially chewed. The quantitative evaluation of mastication efficiency is an important problem for dentists. Many methods have been used to evaluate the mastication efficiency or performance (Oliveira, Shaddox, Toda, Paleari, Pero, Compagnoni, 2014; Torisu, 2017). The sieve method comprises of estimating the volume ratio of food passing the sieve after chewing the measured portion of foods (carrot, peanut) to the total volume of recovered food (Kapur et al., 1964). Chewing gums have been used because they can be produced in large quantity with constant and stable quality. Pigment or glucose released out after chewing was measured to determine the mastication efficiency.

Hard gum is chewed more slowly than soft gum and the slowing is due to a significant prolongation of the opening and occlusal phases. Duration of closing and the vertical excursion of the mandible are not affected even though the masseter muscle activity is prolonged and enhanced. The sensory inputs responsible for this modification of the CPG’s output remain to be identified.

The evaluation of the size distribution of masticated food fragments has also been used to understand the mastication efficiency and flavour release (Kobayashi, Kohyama, Shiozawa, 2010; Moritaka, Yamanaka, Kobayashi, Ishihara, Nishinari, 2019; Olthoff, van der Bilt, Bosman, Kleiszn, 1984; Wang, Yang, Brenner, Kikuzaki, & Nishinari, 2014). See the section 3.3 Instrumental simulation of mastication.

Thus, we can see data on the mastication performance including the mastication velocity from the papers published in dental science. In these papers, the number of chewing, vertical and lateral displacements of jaws have been reported and some papers calculated the average chewing velocity.

However, the other factors such as the sample size, plastic behavior in addition to elastic behavior should be taken into account. Most frequently used mechanical parameters to find the correlation with the chewing behavior including chewing velocity are Young’s modulus and fracture stress, but many other factors influence the chewing behavior. In addition, Meullenet, Finney and Gaud (2002) found that the individual difference among subjects were more important for the different velocities of mastication for cheeses ranging from 16.6mm/s to 39.0mm/s. They did not find correlation between the mastication velocity and the sensorily evaluated hardness.

Therefore, a simple and definite answer to the question ”Does the chewing velocity increase or decrease with increasing hardness (firmness) or the Young’s modulus of a solid food?” cannot be given.

**6.4 Some problems in the sensory evaluation**

There is a good website showing the glossary of sensory evaluation:

https://www.sensorysociety.org/knowledge/sspwiki/Pages/Descriptive%20Analysis.aspx

Hedonic sensory evaluation is usually conducted to know the liking of a specific food, and the evaluation is done by many consumers. Analytical sensory evaluation is done by trained panellists. The training requires a long time (Bourne, 2002; Meilgaard, Civille and Carr, 2016; Rosenthal, 1999; Lawless and Heymann, 2010).

The sensory evaluation of attributes of foods was done during or after the mastication or even before ingestion. By visual, olfactory senses or tactile senses during cutting into pieces using knife and fork or scooping a fluid or gel-like food by a spoon, humans perceive many attributes simultaneously at different stages of consumption.

Time intensity (TI) method (**Lawless**, Heymann, 2010a) became a common method since when a subject could move a cursor with a mouse on the screen of personal computer rating on a general version of the labelled magnitude scale (Bartoshuk et al, 2002). In most cases, a subject concentrates on only one specific attribute and if necessary he/she evaluates another attribute in the same way. Then, another method Temporal Dominance of Sensations (TDS) was introduced in the sensory evaluation (DiMonaco, et al, 2014; Lenfant, Loret, Pineau, Hartmann, Martin, 2009). In this TDS, subjects are instructed to rate the intensity of several attributes related to taste, odour, end texture from the beginning of mastication until swallowing. Since the natural eating speed is different among subjects, rescaled data were usually analysed. Then, another method check-all-that-apply (CATA) was proposed (Ares, 2015; Ares et al., 2013), and recently the same group proposed another new method rate-all-that-apply (RATA) and compared RATA with CATA (Vidal et al., 2018). The liking of food is changing incessantly in the mouth, and the temporal drivers of liking (TDL) was also proposed (Thomas, Visalli, Cordelle, Schlich, 2015).

In most previous studies, only one attribute was rated by subjects as mentioned above. It was thought that subjects should concentrate only one most important attribute. But, in reality, subjects perceive many other attributes simultaneously, and when he/she reports the intensity of the attribute, other perceived attributes are thrown away. This omission of potentially salient rating scales was called dumping effect (Clark and Lawless, 1994). In addition to dumping effect, the rating of similar attributes tends to be added to the score of the selected attribute to be rated because such a rating option is not given to subjects. This inflation of rating caused by the lack of rating options was called halo effect (Clark and Lawless, 1994). In practice, when too many attributes are to be rated the deflation in rating will occur, but too few attributes are to be evaluated, it may also lead to biased result (Lawless and Heymann, 2010b).

The mouth cleansing or re-initialization of mouth condition before the next sample evaluation is done by rinsing with de-ionized water between each stimulus. In some other sensory studies, sparkling water and crackers and tap water taken ad libitum (Liu, Stieger, van der Linden & van de Velde, 2015), non-salty cracker is used for mouth cleansing (Vickers, Morris, Savaria, 2008; Lima et al, 2018) while water was provided for rinsing the mouth in the sensory evaluation of cheeses (Saint-Eve et al., 2015) or of potato soups (Dermiki et al, 2015), or of agar gels containing sweeteners (Miele, DiMonaco, Dell’Amura, Rega, Picone, & Cavella, 2017).

In the fMRI study of the taste and odour perception, a tasteless solution (containing the main ionic components of saliva, 25mMKCl + 2.5mM NaHCO3) was used as a control stimulus. This was administered after 5s of evaluation of the sample solution, and was used as the comparison condition for the taste solution, and allowed non-taste effects such as somatosensory effects produced by liquid in the mouth, and the single tongue movement made to distribute the liquid throughout the mouth (de Araujo, Rolls, Kringelbach, McGlone, & Phillips, 2003; O’Doherty, Rolls, Francis, Bowtell, & McGlone, 2001).

Vickers et al. (2008) found that non-salty crackers achieved the best performance for mouth cleansing in the sensory evaluation of sour taste of orange flavoured beverages. The sourness intensity was found to increase with increasing citric acid concentration. The panellists used non-salty crackers, carrots, or water as mouth cleanser, and the similar discrimination was observed, but the panelists rated the sourness higher after using carrots or water than after using the cracker. In a study of wine astringency, a piece of cookie (the taste was not specified) was eaten, and the mouth was rinsed with ionized water for 10s twice, then panellists waited for at least 20 s before the next sample (Brossard et al, 2016). In hedonic sensory evaluation of fresh cheeses, subjects were instructed to consume a spoonful of plain cottage cheese, a piece of Granny Smith apple, and then a sip of water between each product (Thomas, Visalli, Cordelle, Schlich, 2015). It seems that there is no consensus which method is more reasonable.

When some model gels are used, the sample description is not described in most sensory studies unfortunately. When the physicochemical properties of gelatin are studied, the isoelectric point and average molar mass are reported because without the information of these characteristics, the subsequent measurements and evaluation remain ambiguous. It seems that a laboratory mainly interested in sensory evaluation is not equipped with sufficient instruments required for material characterization. The opposite is true: a laboratory equipped with sophisticated instruments is busy to maintain these instruments, and not gathers the panellists and train them. The collaboration is required for further progress.

The individual difference of subjects, outliers or exceptional members in the assessors, is a difficult problem. Some assessors reported the increase of the banana flavour (isoamyl acetate, IAA) when the sucrose solution was replaced by water although such assessors are not the majority (Hort and Hollowood, 2004). Tasters, non-tasters and super tasters reported in the study of bitter taste (Bartoshuk, Duffy, Miller, 1994) has been studied extensively from the viewpoint of ethnicity, gender, age, phenotype by many research groups (Yang, Williason, Hasted, Hort, 2020). Since some experienced assessors seemed to be able to separate the stimuli involved in flavor perception of IAA-sucrose-water and thought to be not suitable in the study of cross modality (Hort and Hollowood, 2004).

**Conclusion**

Dominant role oftexture in the food ｏｒａｌ processing was described in relation with physiological basis and psychological palatability, which must be further interacted with traditional food science and technology. As is well recognized, food consists of multi-components and is in non-equilibrium state, which needs to be analysed from multi-angle approach. The interaction and collaboration are in progress and must be further accelerated to get more insight and find a better way. We must not hesitate to cross the border between different disciplines as stated by Scott-Blair (1950) who encouraged scientists not to be afraid to cross frontiers.

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