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EVALUATION OF THE SENSORY CORRELATION BETWEEN TOUCH SENSITIVITY AND THE CAPACITY TO DISCRIMINATE VISCOSITY

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ABSTRACT

The capacity to discriminate the viscous nature of food materials is critically important in the sensory evaluation and subsequent perception of food texture and acceptability. It is generally assumed that this capability is closely linked to individual's tactile sensitivity, which in itself is a function of the individual's specific capabilities due to experience, age, lifestyle and health status for example. However, no experimental evidence is yet available to validate or disprove this assumption. By comparing the touch sensitivity and the capability of viscosity discrimination among individuals (using finger and tongue sensory perception), this work aims to establish if a correlation exists. Semmes-Weinstein monofilaments were used for touch sensitivity tests of the index fingers and tongue surfaces. A series of syrup solutions were prepared to give a wide range of viscosities with a viscosity scale factor of 1.2 ± 0.009. A total of 30 healthy subjects (16 female and 14 male; mean age 29.9 ± 9 years; mean body mass index 22.5 ± 2.9 kg/m^2) participated in this study. A similar touch sensitivity threshold, 0.023 and 0.021 g, was observed for the index fingertip and for the tongue, respectively. However, the tongue appears to be more sensitive to touch than the fingertips when the force range they cover was compared. The viscosity discrimination threshold was found to be approximately 53% for the index fingertip and around 47% for the tongue. By comparing individual capabilities of viscosity discrimination against touch sensitivity, no significant correlation was observed between the two factors. The results from this work suggest that the capability to discriminate viscosity differences is more likely attributed to experience and is little influenced by one's physiological capability of tactile sensation, e.g., the touch sensitivity.

PRACTICAL APPLICATIONS

The capability to discriminate differences in viscosity and the subsequent perception is an important factor for food texture appreciation. Establishment of the underlying factors that characterize the variation in the ability for such discrimination across individuals is not only critically important for our fundamental understanding of the viscosity perception but is also hugely important for the food industry in development of new food products, and in particular for specific food design for individuals with special needs, e.g., elderly, dysphagia patients, etc. Differential threshold for certain tastes and aroma compounds has been investigated. However, little has been reported in the literature about the tactile interpretation of viscosity sensation and perception. Findings from this work could provide new insight for researchers in the food industry and in food development by giving them flexibility to redesign their ingredients especially the one that has thickening

effect on the product viscosity. Methodologies used in this experiment could also be applied for general food sensory studies in establishing relationships between sensory psychology and sensory physiology and especially the threshold studies with a similar approach of finding just noticeable difference values of any stimuli. The method could also be applicable to sensory capability studies of some particular groups such as elderly people to assess how weakened physiology affects their sensory capability.

INTRODUCTION

The textural properties are often used by consumers as an important indicator of the quality of the food and play a critical role in influencing consumer's preference and acceptability of a food product (Foegeding *et al.* 2003). However, consumer's perception of food texture could be very complicated, as has been shown recently by Hayakawa *et al.* (2013), and the prediction of consumer's texture perception is proved to be more challenging. The use of instrumental methods for reliable texture assessment has been a major focus of food texture studies for decades. Compression deformation via a texture analyzer and shear deformation using a rheometer techniques are the two most widely used approaches for the characterization of textural features, especially those that are closely linked to the mechanical/rheological properties of the food, such as hardness, firmness, viscosity, thickness and springiness (Chen 2009; Kim *et al.* 2012; Chen and Opara 2013). The principles of tribology and lubrication studies have also been recently applied to elucidate textural features that are closely associated with relative surface movements such as smoothness, roughness, slipperiness and even creaminess (Malone *et al.* 2003; Prakash *et al.* 2013; Chen *et al.* 2014). Despite the advantages of instrumental objective approaches in producing robust and reliable results for texture characterization, the interpretation of instrumental results has always been difficult because of the lack of causality between instrumental results and oral perception in most cases (Guinard and Mazzucchelli 1996).

The poor correlation between instrumental characterization and oral perception of the consumers has always been and still remains a big challenge for food scientists (Karel 1997). Many taste and aroma sensory attributes have specific gustatory and olfactory receptors in the human anatomy, which have been identified as directly associated with their detection and sensation. So far, the mechanisms of food texture sensation and perception are not as well understood as those of the aroma or the taste (Kilcast and Eves 1991). Most sensory scientists tend to agree that various mechanoreceptors function as sensory detectors, collecting texture-related information and conveying them to the brain for sensory analysis. However, the neurological principles of this process are still poorly understood (Guinard and Mazzucchelli 1996).

A possible explanation of the poor correlation between human and instrumental texture characterization is probably due to the very different scaling mechanisms used by human beings and by physical measurement instruments (van Vliet 1988). Human sensory scaling and discrimination have been a major focus of psychophysical studies for over a century. Weber conducted one of the earliest studies in this area in 1834, in which he found that human's capability in discriminating weights was by percentage difference rather than by absolute amount. He observed that a 5% difference is essential for weight discrimination (Batschelet 1979). Based on these observations, a theory of proportional threshold for sensory perception was proposed as Weber's law. It states that the magnitude of a just noticeable difference (JND) of a sensory feature (ΔI) is proportional to its own intensity (I), or

$$\frac{\Delta I}{I} = k \tag{1}$$

where k is a constant and is often called the Weber's fraction or Weber's ratio. In this study, k value will be named as the viscosity ratio. Some scientists suspect whether an instrument measures the same thing that sensed by human being. This is, of course, another possible reason for the poor correlation between human perception and instrumental characterisation.

Even though Weber's law is applicable to many sensory attributes, the factors that propagate the wide variation of sensory sensitivity among human population have yet to be explained. Studies have revealed that groups of individuals will respond with a wide range of JND values and their corresponding Weber's ratios for all sorts of sensory properties. This may be due to the difference between the sensory physiology of individuals (the physiology factor) or due to the different life experiences that shape an individuals' sensory capability (the psychological factor). Obviously, it may also be a combination of the two attributes. General speculation is that tactile sensitivity has an important influence on an individual's capability in discriminating textural properties of a food. Following this hypothesis, many well-designed investigations have been conducted in the past few decades but no solid experimental evidence is yet available to either substantiate or disapprove the relationship between the two. The earliest of the studies of this type was probably the one leading to the well-known master curve between the oral shear rate and the viscosity perception (Shama and Sherman 1973; Shama *et al.* 1973).

By investigating the capabilities of subjects in relation to touch detection and viscosity discrimination by either the fingertip or the tongue, this work aims to obtain experimental evidence to test whether a relationship exists between human sensory capability of viscosity discrimination and tactile sensitivity. The fingertips and the tongue are the most sensitive tactile organs of human body and were therefore used in this work for texture (viscosity) detection and discrimination. Viscosity was chosen for sensory analysis because of the critical role it plays in textural sensation of many food products, and more importantly, because of the availability of reliable instrumental quantification for its physical intensity.

Tactile sensation could implicate different detection modes such as touch force (time dependent in compression or shear), pressure (space dependent), space displacement (proprioception) and the corresponding combined effects inherent in vibrations or distortions. All of these tactile modes are believed to contribute to our sensation and perception of the external contact and in particular of the textural properties of the contacting object. In this work, sensation due to touch force will be used as a representative capability of tactile (touch) sensitivity. Semmes-Weinstein monofilament (SWM) test, a commonly used technique for tactile sensitivity assessment, will be used for touch sensitivity tests (Wiggermann *et al.* 2012). The technique applies different monofilaments of a wide range of stiffness to allow the threshold determination of the touch sensation.

MATERIALS AND METHODS

Food Samples

Lyle's golden syrup (Lyle's Golden Syrup Tate & Lyle, Nottinghamshire, U.K.) was purchased from a local supermarket and used as samples for viscosity discrimination assessments. Golden syrup was stored in its original metal can container at ambient temperature and was used prior to the indicated best-before date. Test samples were reconstituted into a series of solutions with required viscosities by simply diluting the syrup with distilled water.

Assessors

A total of 30 assessors (16 female, 14 male) were recruited for this study. All subjects were non-smokers and in good health status. They reported no medical complications, no eating disorders and no oral diseases, and are not suffering from any skin problems. Subjects were also not on specific diets. Subjects were aged between 19 and 49 years old (with a mean age of 29.9 ± 9 years) and had a mean body mass index (BMI) of 22.5 kg/m^2. All subjects were recruited from the campus of the University of Leeds and were either students or university staff. Written consents were obtained from each assessor prior to the test. During the initial introduction, assessors were informed of what would be involved in the test and the exact procedure. However, no more information was given about the purpose of the investigation. Permission was obtained from the faculty ethic committee (MEEC 12-013) and all test procedures followed the ethical rules and regulations set by the University of Leeds, U.K.

TABLE 1. PROPERTIES OF CONSTITUTED SYRUP TEST SAMPLES

Sample number	Actual viscosity (mPa·s)	Actual concentration (%)	Viscosity difference from the reference (ΔI)	Viscosity ratio ($\Delta I/I$)
*1	1.05	6.7	0	0
2	1.18	12.2	0.12	0.12
3	1.48	20	0.43	0.41
4	2.09	30	1.04	0.99
5	2.56	33	1.51	1.44
6	2.78	37	1.73	1.65
7	3.23	40	2.18	2.08
8	3.61	42.4	2.56	2.44
9	4.25	45.6	3.20	3.05
10	4.95	48.4	3.90	3.71

* Reference sample.

Rheological Measurements

The dynamic viscosities of golden syrup samples were measured using Kinexus rheometer (Malvern Instruments, Ltd., Worcestershire, U.K.). Measurements were conducted at 25°C using a double gap geometry (DG25 geometry, 26.25-mm cup diameter, 24-mm bob internal diameter, 25-mm bob external diameter and 57.5-mm wall height). Viscosity value should remain the same for a wide range of shear rates due to the Newtonian nature of the golden syrup. Viscosity tests were carried out three times and the average viscosity was obtained from these tests (Table 1).

Touch Sensitivity Tests

SWM Touch Sense sensory evaluators (see Fig. 1) were used for touch sensitivity tests. The test kit was purchased from North Coast Medical, Inc. (Gilroy, CA). The set consists of 20 monofilaments designed to provide a non-invasive evaluation of cutaneous sensation levels throughout the human body. The touch force ranges from as low as 0.008 g

FIG. 1. TOUCH SENSATION TEST KIT CONSISTING OF 20 SEMMES-WEINSTEIN MONOFILAMENTS

to a maximum value of 300 g, arranged in logarithmic intervals. According to the manufacturer's specifications, each Touch-Test sensory evaluator (the monofilament) had been individually calibrated to deliver its targeted force within an accuracy of 5% of the given value (North Coast Medical Inc. 2013).

The index fingertip of the dominant hand and the tongue were chosen for touch sensitivity tests. Before the test, subjects were asked to have their hand washed with soap and water and dried with a paper towel. The tongue was cleaned by rinsing the mouth with fresh water twice. Subjects were then asked to sit comfortably in a relaxed position. For the fingertip touch test, subjects were asked to rest the hand on a bench and release fingers in a relaxed manner. For the tongue touch tests, subjects were asked to open their mouth and gently extend their tongue outside the mouth in a manner they found most comfortable. The touch position was selected at the front central position, about 1.5 cm from the front tip. A Touch Sense monofilament was pressed perpendicular to the surface of the tongue until the filament bowed for approximately 1.5 s. The pressing force increases to a maximum when the filament starts to bend, as illustrated in Fig. 2. Subjects were blindfolded to prevent them from gathering any visual clues and were asked to give a signal if they sensed a touch of the target position (fingertip or the tongue tip). Tests were started with a monofilament that applies a force of 1 g and then continued in a descending order towards the lowest available force of 0.008 g. Tests stopped when the subject failed to give positive response to two consecutive monofilament touches. The last positively detected force was then taken as the threshold of touch sensitivity. Between each test, the monofilament fiber was cleaned with an antibacterial wipe. All tests were conducted in a purposely designated sensory laboratory within the food science building at the University of Leeds.

Viscosity Discrimination Tests

JND sensory tests were also conducted in the same sensory laboratory as for touch sensitivity tests by using two-alternative forced choice (2-AFC) method. The purpose was to determine the human capability of viscosity discrimination by using the fingertip and the tongue. A series of syrup samples were carefully prepared by diluting a certain amount of syrup with distilled water by using a viscosity scaling factor of 1.2, which is equal to a 20% increase in viscosity between the samples (see Table 1). Syrup solutions have a light yellowish appearance, which deepens slightly with increased concentration. Sample 1 has the lowest viscosity and was used as the reference sample in order to have wide range of differences in the Weber's ratios. Participants were served with nine pairs of samples (constant reference versus test sample) and they were asked to report if they sense the viscosities as the same or different. In particular, viscosity discrimination tests were applied on the fingertip and tongue. For fingertip tests, subjects were blindfolded in order to exclude any prior visual information about the fluid samples. A sample of around 0.2 mL was placed between the index fingertip and the thumb, and the subject was asked to gently move fingers and apply a shear to sense the viscosity and to make a judgment as to whether the viscosity was the same or different from the reference sample. Between testing the samples, the reference sample was also

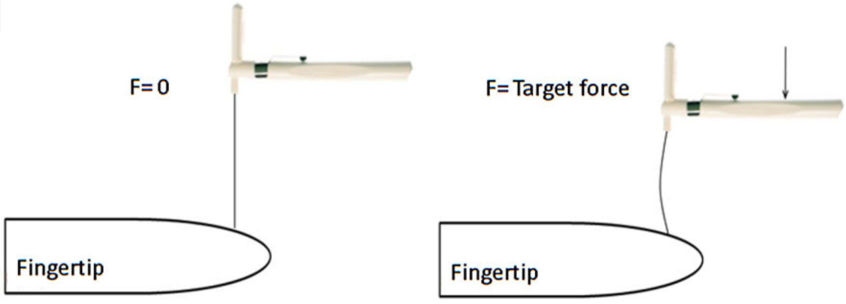

FIG. 2. ILLUSTRATION OF TOUCH SENSATION TEST METHODOLOGY
The filament is pressed in a perpendicular direction against the target surface. The pressing force continues to increase until it reaches a maximum when the filament starts to bend.

repeatedly sensed to ensure that the subject did not lose the perception of the reference viscosity. Fingertips were cleaned with a wet tissue paper and then dried with a paper towel between the samples. For tongue tests, no blindfold was applied and 1 mL of syrup solution was given to assessor for each sample. Subjects were able to see the samples so that they could safely deposit samples on the middle of the tongue surface and apply shearing with the tongue against the palate few seconds when subjects feel that a judgment can be made. Since test samples have a Newtonian character and their viscosity have little dependence on the shear rate, no specific instruction was given about the moving speed of the tongue during the sensory tests. During tongue viscosity discrimination tests, the test room was lighted with a red light in order to avoid color differences between the test samples to be detected by the participants. Water was provided to cleanse the palate between the tests. Samples were arranged in an ascending order of viscosity without any prior knowledge of the subjects. Assessors were asked whether they could sense any difference between the reference sample and the test sample. Tests ceased when the subject gave three consecutive correct detections of viscosity difference and the last positive answer was taken for the calculation of the JND value. However, during the tongue viscosity discrimination tests, the increasing concentration leads to an increasing sweetness of the sample and causes limitation for this study. The taste matching of the samples was not applied due to the hypothesis of testing the Newtonian material. Hence, the participants were asked to avoid taste difference as much as they can and focus more on the consistency difference. Cumulative JND against population was then tabulated by calculating the added number of correctly detected participants, and the median JND value (50%) was taken as the population median for viscosity JND.

Statistical Analysis

Statistical analysis was conducted using XLSTAT 2014.3.04 statistical software (Microsoft, Mountain View, CA). For data analysis in particular, mean, median, standard deviation and coefficient of determination (R^2) values were calculated for age and BMI. Mann–Whitney *U*-test was applied to calculate the differences between the two experiments of touch sensitivity and viscosity discrimination.

RESULTS

Figure 3 summarizes the touch sensitivity of the index fingertip (Fig. 3a) and the tongue (Fig. 3b) in the form of population distribution. Population variation in touch sensitivity is clearly evident for both the fingertip and the tongue. It appears that none of the assessors from the population appears to be able to detect a touch force below 0.008 g, which is the minimal force available from the current technique. At the higher end, the fingertip had touch sensitivity as high as 0.6 g, while the tongue surface sensitivity showed much narrower distribution, with a highest touch force of 0.16 g.

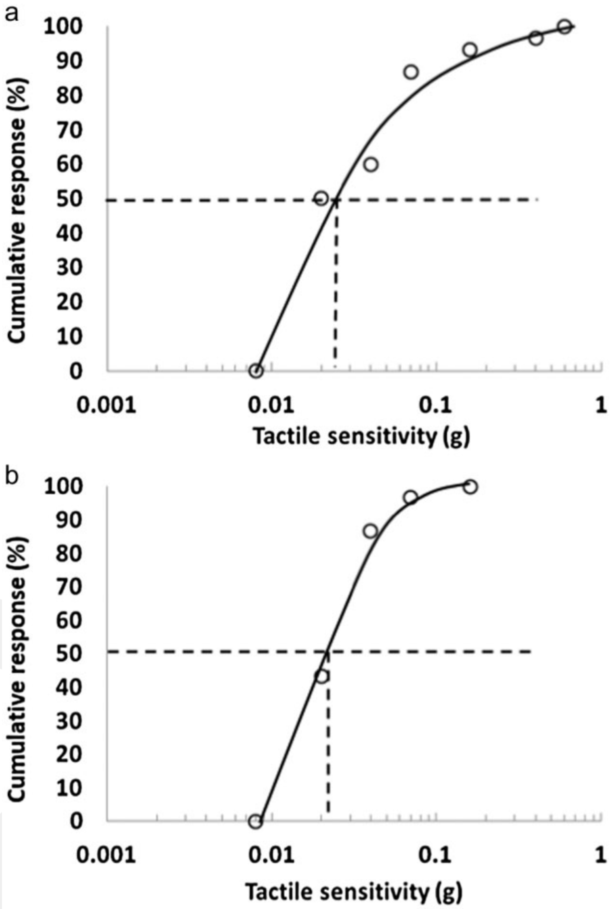

FIG. 3. CUMULATIVE RESPONSES OF SUBJECTS SHOWN AS POPULATION PERCENTAGE AGAINST THE TOUCH SENSITIVITY: (A) THE INDEX FINGERTIP AND (B) THE TONGUE
The two dashed lines indicate the threshold value at the 50% population value. The solid line was drawn to guide vision.

It is a general practice to use the value at the 50th percentile population distribution (i.e., median) as the representative value for the population, or the so-called population threshold (Lawless and Heymann 1998). Based on this approach, we can estimate that the touch force threshold for fingertip is around 0.023 g (Fig. 3a). Similarly, the touch force threshold for the tongue is around 0.021 g (Fig. 3b), with no statistically significant difference from that of the fingertip (*P* value = 0.598).

Figure 4 summarizes the subject capabilities of viscosity discrimination by using the index fingertip and the tongue.

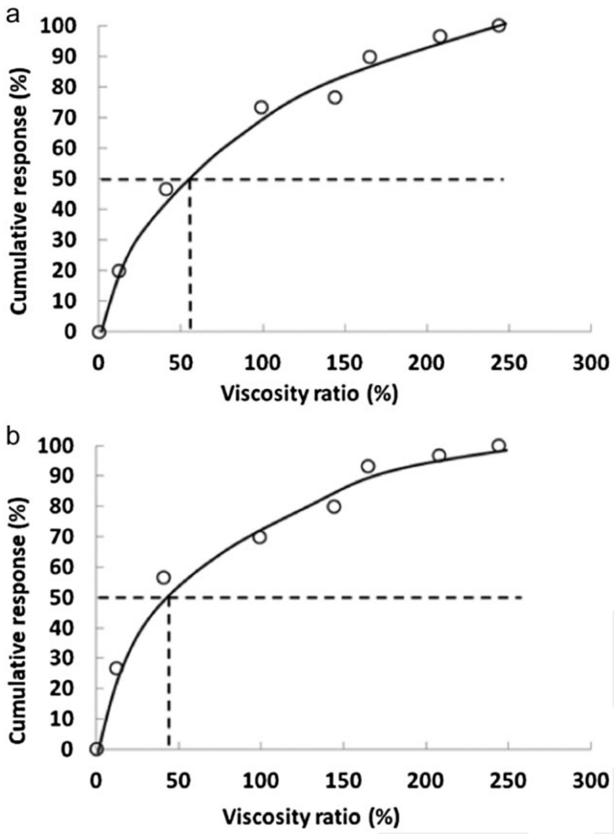

FIG. 4. TEST OF JUST NOTICEABLE DIFFERENCE (JND) OF FLUID VISCOSITY
Cumulative responses of subjects is plotted against the the viscosity ratio of the test sample against the reference sample (6.7%): (a) JND by the index fingertip and (b) JND by the tongue.The two dashed lines indicate the threshold value at the 50% population value. The solid line was drawn to guide vision.

The population (percentage) who could discriminate viscosity difference of syrup solutions from the reference is plotted as a cumulated population percentage against the viscosity ratio between the sample and the reference. Using the sample value at 50% population for the JND values for both the fingertip and the tongue, the authors estimate that the median fingertip viscosity JND is about 53% (Fig. 4a) and the JND of viscosity discrimination by the tongue is smaller at about 47% (Fig. 4b). Statistical analysis also showed that the tongue has significant difference in viscosity discrimination capability from that of the fingertip (*P* value = 0.027).

DISCUSSION

The main aim of this study was to investigate if a correlation exists between the touch sensitivity and the capacity to discriminate differences in viscosity. It has been generally accepted that viscosity perception and discrimination is achieved through mechanisms of tactile sensation, and therefore, it is speculated that an individual who has a higher tactile sensitivity may have a better ability to discriminate textural properties, including the viscosity of materials. Golden syrup solutions were chosen for viscosity sensation and discrimination in this work. This choice was made based on two considerations: First, syrup is a common food ingredient that is widely used in food applications and is well-known by consumers all over the world. Second, and more importantly, syrup solutions have a near-Newtonian behavior; their viscosity is little influenced by the rate of shear deformation. Therefore, the different manner in which individuals handle a fluid should have a minimal influence on their viscosity perception.

SWMs were adopted for tactile sensitivity tests on both the index finger and the tongue surface. Even though monofilaments were not considered reliable enough for neurological examinations, they have been proven to be valuable in assessing touch sensation for general purposes and nerve treatments (Lundborg 2000; Schreuders *et al.* 2008). The technique is commonly seen as an effective method for touch sensation and applications of the technique as a standard test for the determination of touch sensation thresholds, which have been reported in the literature (Bell-Krotoski and Tomancik 1987; Jerosch-Herold 2005). Even though the technique has been applied to various parts of human skin, to the best of the authors' knowledge, no application of the method has been reported in the literature for a tongue tactile sensitivity test. In the present study, these monofilament tests were adopted for the first time to study touch sensation of both the index finger and the tongue simultaneously.

Fingertips and the tongue are believed to be the most tactile sensitive parts of the human body (Schmidt 1986). Fingers (hand) are often used as our first tactile detectors to obtain textural, geometrical and thermal information about a contacting object. In terms of foods, our tongue is the most important detecting device for the sensation of textural properties as well as other sensory features of food. The results obtained from this work confirm that human beings are highly sensitive to touch. Over half the population of the tested subjects were able to sense a touch force below 0.23 g by the index fingertip and 0.21 g by the tongue (Fig. 3). The threshold of the touch sensitivity is more or less in the same magnitude for both surfaces. We noticed that even though the touch threshold of the index fingertip seems to be marginally higher than that of the tongue, statistical analysis reveals no significant difference (*P* value = 0.598) between the two tactile modes. Nevertheless, the touch sensitivity for the fingertip has a much wider distribution than that of the tongue. For example, the least tactile sensitive tongues could detect a force of only 0.16 g, but the least touch sensitive fingertip was found to be unable to sense a touch force of 0.6 g. It is not evident as to what is the cause of this variation in the touch sensitivity among individuals. However, individual physiological factors are believed to be implicated as the underlying cause. Variation (density) of mechanoreceptors per unit area among individuals could lead to very different skin sensitivity to mechanical stimulus. Another possible reason could be due to the gradual wear or damage of skin surface, which may be related to lifestyle, e.g., occupation. In our case, rougher hand skin was visually evident for few subjects who showed reduced touch sensitivity.

The results obtained from our study agree well with those reported by previous studies in the literature. Joris Hage *et al.* (1995) reported a touch sensation threshold for the index finger in the range of 0.008–0.6 g. Another research by Gillenson *et al.* (1998) also reported a similar range from 0.008 to 0.07 g for the touch force threshold of the index finger. The agreement between our results and these literature data suggests that the experimental procedure adopted in this work is a reasonable and reliable approach for the assessment of tactile sensitivity.

There has been no reported literature on the tactile sensitivity level of the human tongue. Our results indicate that the human tongue has a very high tactile sensitivity, at least at the same magnitude of the sensitivity of the fingertips. The average touch threshold for the tongue in our samples had no significant difference (P value = 0.598) from that of the index fingertip but does have a much narrower distribution, with a range of 0.008–0.16 g for the tongue against 0.008–0.6 g for the fingertips.

Figure 4 plots the cumulative population distribution against the viscosity ratio (see Table 1). By choosing the 50% median threshold, we estimate the expected JND value (Weber's fraction) for the viscosity perception in a wider population. Based on the results shown in Fig. 4, one could estimate that for the index fingertip, the Weber's ratio is around 53%, while for the tongue surface, the Weber's ratio is at about 47% (P value = 0.027). This implies that the human tongue could be more sensitive in discriminating fluid viscosity than the fingertips, despite the fact that the touch sensitivity is statistically not significantly different. The difference in capability of viscosity discrimination between the tongue and the fingertip is somewhat surprising. One may speculate that the tongue is probably more accustomed to dealing with fluid food than the fingers and therefore the capability of viscosity sensation is enhanced by the daily experience of food. In other words, learning and experience play an important role.

By plotting the capacity to discriminate viscosity against touch sensitivity for both fingertip and tongue (Fig. 5), it is clear that in the case of the participants tested, the human capability for viscosity discrimination varies substantially between individuals. More importantly, this variation in capability appears to have little correlation with the touch sensitivity. This is true for both the fingertip and the tongue, where the R^2 values were only 0.059 and 0.0296, respectively, showing no correlation. Based on these results, one may conclude that there is no direct correlation between the touch sensitivity and the capacity to discriminate differences in viscosity.

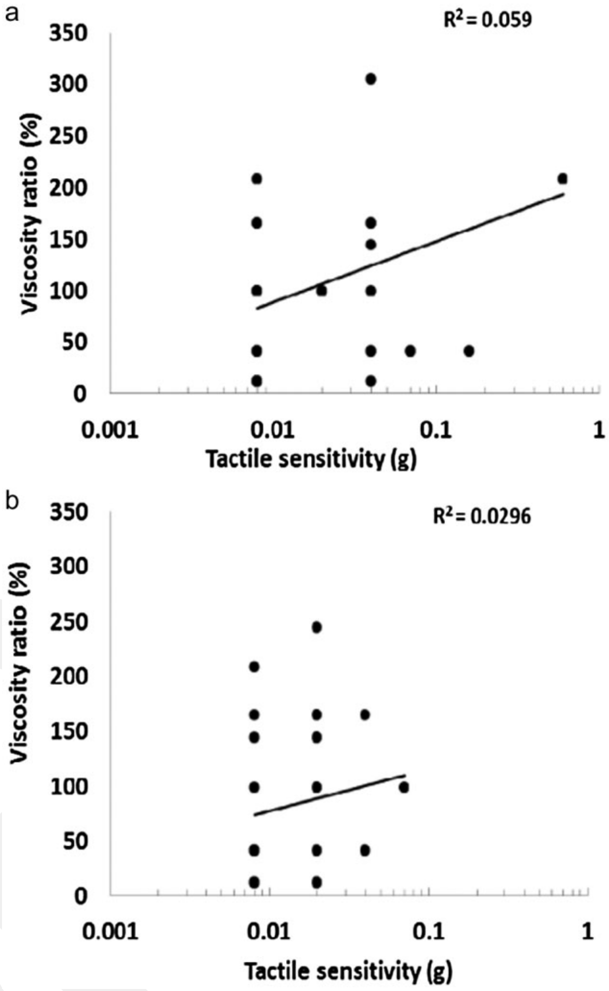

FIG. 5. CORRELATION BETWEEN THE CAPABILITY OF VISCOSITY DISCRIMINATION AND THE TOUCH SENSITIVITY: (A) BY THE INDEX FINGERTIP AND (B) BY THE TONGUE
Correlation coefficient R^2 is given in the figure.

To discriminate differences in fluid viscosity is clearly a difficult task and it is not surprising therefore to observe variation in this capability among individuals. The underlying reason for population differences of viscosity perception is still not understood and resides on complex physiology and psychophysical relationships and our corresponding sensation and perception (Guinard and Mazzucchelli 1996). Viscosity is a major textural feature and its sensation and perception is much more complicated than that of taste and aroma since for the latter cases, there are known specific sensory receptors directly responsible for detecting the taste and aroma stimuli. However, for textural features, there is no such direct correspondence between the sensory receptors and the textural properties. Even though mechanoreceptors are known to be largely responsible for the sensation of textural properties, it is still not entirely clear how these receptors operate and the mechanisms that transfer the associated sensation. Additionally, the physiological differences between the individuals, such as the saliva composition, mouth geometry or the dental status, are very likely to cause the low correlation between these tests. It is therefore not surprising that there have been very few studies on the physiological principles governing food texture sensation. As such, there are no available independent quantitative data to compare with our findings. However, we notice that Fazzalari (1978) has investigated human sensitivity of taste discrimination and found a Weber's ratio of 0.65 (or 65%) for sucrose taste, 0.047 (or 4.7%) for saltiness and 0.03 (or 3%) for sourness. This suggests that humans are probably more capable in terms of viscosity discrimination than they are in detecting difference in sweetness, but much less so than in saltiness and sourness discrimination. One of the latest research carried out by Steele *et al.* (2014) showed that the 67% increase in the viscosity of xanthan gum thickened (non-Newtonian) honey nectar sample was detectable by tongue, which shows similar pattern with our findings.

Our finding of the no correlation between touch sensitivity and the capability of viscosity discrimination is somewhat contrary to the general belief. While this finding requires confirmation from other independent studies, we consider it to be a reasonable finding based on a logical approach for the following reasons; first, viscosity sensation is a dynamic process that involves the application of a shear force applied parallel to the direction of deformation rather than a compression force exerted perpendicularly to the direction of deformation. Based on this consideration, touch sensitivity alone may have very limited relevance to viscosity detection. Second, there are slow adapting (SA) and rapid adapting (RA) mechanoreceptors responsible for the detection of tactile stimuli. The former is responsible for detecting a continuous application of external mechanical stimuli, while the latter is responsible for the on-off application of such stimuli. In most areas of the human skin, SA accounts for around 67% of the total mechanoreceptors. But on the tongue surface, it was found that around 67% of mechanoreceptors are RA type (Bukowska *et al.* 2010), suggesting that the tongue is much more adapted for detecting changing external stimuli rather than for sensing a continuously applied stimulus (static). Third, the viscosity of a fluid relates to the speed of displacement under an applied deformation force. Therefore, surface displacement is also an essential factor for viscosity sensation. In other words, one's capability in discriminating viscosity will rely on his/her capability in space discrimination, speed discrimination and force (stress) discrimination.

While experimental evidence from the current study is persuasive, possible limits of the experimental design should be noted. First, fluid viscosity is normally very sensitive to temperature changes. However, in this work, the instrumental viscosity was measured at 25°C, while the fluid for sensory tests was provided at room temperature (22 ± 2°C) and then sensed by a body at 37°C; therefore, heating of the sample would occur immediately by some unknown rate. This inconsistency in the experimental design was acceptable because of the uncertainty of the real oral temperature for viscosity sensation. Furthermore, it has been reported that skin temperature is always lower than the body temperature and the exact intra-oral temperature inside human mouth could vary from subject to subject (Engelen 2012). Therefore, to avoid further complication in experimental design, a simple approach was adopted. In this case, a temperature difference between instrumental tests and in-oral sensation is of course predicted. However, we would also expect that the temperature (as well as the viscosity) variation should occur in a very similar scale for all samples and should not cause significant deviation in viscosity discrimination.

Another issue to be noted is the limit of the SWM device itself. This device assesses tactile sensitivity based on the force rather than the stress (pressure). The SWM evaluators have a range of diameters to give desirable mechanical strength against bending. A different diameter of the filament implies that the applied pressure could be in very different scale from that described by the force. From our own measurements, the 0.008 g filament has a diameter of 0.02 mm, and for the 0.6 g filament, a diameter of 0.2 mm is measured. However, the diameter sizes of all monofilaments used in this work are significantly below the threshold of the human capability for tactile space discrimination as human proprioception on the fingertip has been found to be in the order of 2 mm (Schmidt 1986). This suggests that spatial factor should not play a significant role in the current touch sensitivity tests considered.

CONCLUSIONS

Human touch sensitivity has been examined using the SWM device. It was found that within the participants tested, the fingertip and tongue have very similar touch sensitivity, with threshold values of 0.23 and 0.21 g, respectively. However, the touch sensitivity for the fingertip has a much wider variation than that of the tongue, which ranges from 0.008 to as high as 0.6 g for the fingertip and from 0.008 to 0.16 g for the tongue. However, the capacity to discriminate viscosity was found to be significantly different between the fingertip and the tongue based on viscosity JND tests. The Weber's ratio was calculated to be 53% for the fingertip and 47% for the tongue. Further analysis of individual capability for viscosity discrimination against touch sensitivity showed no correlation between the two factors. This may suggest that viscosity discrimination may be developed largely through experience that may not necessary be identical to that involved in touch sensitivity.

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