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A new sensory sweetness definition and sweetness conversion method of five natural sugars, based on the Weber-Fechner Law

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ABSTRACT

This study's aim is to establish a new sensory sweetness definition and conversion method for five sugars. A "closed-type" question based on triangle test and paired comparison was used for sensory evaluation. The absolute threshold and nine sensory difference threshold values were determined and used to generate a sweet sensory difference strength curve. Defining absolute threshold of sucrose sweetness as 1, the sucrose sweetness at any concentration could be calculated *via* the curve. After taking the logarithm of each curve, sweetness index was calculated as 1, 1.12, 0.94, 1.29, and 1.25 for sucrose, glucose, fructose, lactose and maltose, respectively. Based on this, each sugar concentration and sweetness could be converted and calculated. Single sugar and mixed-sugars sweetness comparison experiments verified the new sweetness index and sweetness values were more accurate (83.3–100%) than those reported in previous studies. Therefore, this new definition and conversion method established more reliable references for sweet taste sensory applications.

KEYWORDS: sugar, sensory sweetness, sweetness convert, sensory sweetness difference strength curve, sweetness index

1. Introduction

Human taste sensation consists of five taste qualities: bitter, sour, salty, sweet and umami (Beauchamp, 2016), with sweet taste considered to be the most essential and desirable taste quality for humans (Divert, Chabanet, Schoumacker, Martin, Lange, Issanchou, et al., 2017a, 2017b; Garneau, Nuessle, Mendelsberg, Shepard, & Tucker, 2018; Pelletier, Lawless, & Horne, 2004; Pfeiffer, Boulton, & Noble, 2000). Infants preferred sweet taste over water at 3, 6 and 12 months (Schwartz, Issanchou, & Nicklaus, 2009).

Mono- and di-saccharides, such as sucrose, glucose and fructose, are a part our daily diet because these sugars are often used as additives in foods (Carocho, Morales, & Ferreira, 2017; Edwards, Rossi, Corpe, Butterworth, & Ellis, 2016; McMahon, Diako, Aplin, Mattinson, Culver, & Ross, 2017). These sugars are known as natural sweeteners because all are derived from natural sources, such as honey, sugar cane, and beet, and have caloric values of 4 kcal/g on a dry weight basis (Grembecka, 2015; Sardesai & Waldshan, 1991). Excess ingestion of these natural sweeteners increases energy intake, which can lead to overweight and chronic diseases, such as obesity and diabetes (Sardesai & Waldshan, 1991).

Over the years, the food industry has discovered several kinds of alternative intense sweeteners, which offered consumers sweet taste but without the calories found in natural sweeteners (Chattopadhyay, Raychaudhuri, & Chakraborty, 2014). Known as artificial sweeteners, some of these intense sweeteners include sucralose, saccharin, and aspartame. Natural and artificial sweeteners have their own sweet taste sensation intensity or sweetness in humans (Choi & Chung, 2015; Dubois, Eric Walters, Schiffman, S. Warwick, J. Booth, D. Pecore, et al., 1991). Sweetness is a major contributor to human palatability and appetite (Sørensen, Møller, Flint, Martens, & Raben, 2003) and one of the most important aspects in some foods, including fruit juice and soft drinks (Clausen, Pedersen, Bertram, & Kidmose, 2011; Goldenberg, Yaniv, Kaplunov, Doron-Faigenboim, Porat, & Carmi, 2014; Haseleu, Lubian, Mueller, Shi, & Koenig, 2013; Ma, Yang, Laaksonen, Nylander, Kallio, & Yang, 2017).

In previous studies, sweetness for sweeteners was measured in relation to sucrose as the reference sugar. However the concentration of sucrose varied between these studies. Some studies used a sucrose solution of 30 g L^{-1} at 20 ºC as the reference sugar and defined its sweetness as 1 (Carocho, Morales, & Ferreira, 2017), whereas in other studies, sucrose concentration was 10% (Chattopadhyay, Raychaudhuri, & Chakraborty, 2014; Grembecka, 2015; Howard G. Schutz & Francis J. Pilgrim, 1957). Similarly, previous studies varied in defining the relative sweetness of natural sweeteners compared to sucrose: relative sweetness for glucose (0.5 or 0.75), fructose (1.5–1.8, 1.1–1.5, or 1.7), lactose (0.2–0.4 or 0.15), saccharin (300 or 240–300), and sucralose (600 or 400–800) (Carocho, Morales, & Ferreira, 2017; Chattopadhyay, Raychaudhuri, & Chakraborty, 2014; Grembecka, 2015; Sardesai & Waldshan, 1991). There is no unified sweetness and relative sweetness standard for researchers and the food industry and it may lead to incompatible research results and unpalatable products.

In the majority of sensory evaluation studies for sweetness of sweeteners, researchers preferred to use the direct quantitative estimation method (Stevens, 1987). In this method, subjects were asked to taste sweetener solution and assigned a sweetness number or selected a point on a rating scale (Camacho, van Eck, van de Velde, & Stieger, 2015; Choi & Chung, 2014; Moskowitz, 1970; Paixão, Rodrigues, Esmerino, Cruz, & Bolini, 2014; Howard G. Schutz & Francis J. Pilgrim, 1957; Stone & Oliver, 1969). Although these subjects were trained before the evaluation, the question–answer format of direct quantitative estimation method is an "open type" question where results might fluctuate based on the state of the subject during different experiment periods.

In this study, we used a "closed type" question based on the triangle test method and paired comparison test method. This type of question format offered better judgment stability over the course of sensory evaluation. We evaluated both the sensory sweetness and sweetness conversion of five natural sweeteners (sucrose, glucose, fructose, lactose and maltose) based on the Weber-Fechner law. Comparison experiments of single sugar and mixed sugars were also evaluated, to verify the new definition of sweetness and conversion method established in this study.

2. Materials and methods

2.1. Chemicals

Sucrose, glucose, fructose, lactose and maltose were purchased from Sinopharm Chemical Reagent Co., Ltd (China). All the chemical reagents were used as received. All solutions were prepared using ultrapure water, resistivity of 18.2 MΩ·cm obtained from a Millipore system.

2.2. Test Samples Preparation

The sucrose, glucose, fructose, lactose and maltose absolute threshold test samples were prepared in ultrapure water. Each sugar's absolute threshold test sample's compared sample was the ultrapure water. The test sample concentrations were in weight/volume and are listed in Supplementary Table 1. Before the sensory analysis, all samples were kept at a temperature of 20 ^{o}C.

The sucrose, glucose, fructose, lactose and maltose difference threshold test samples were prepared in ultrapure water. In the sucrose first difference threshold test experiment, the compared sample concentration was its absolute threshold value. At the same time, the sucrose first difference threshold test sample concentrations were 115%, 120%, 125% and 130% of its compared sample concentration. In the sucrose second difference threshold test experiment, the compared sample concentration was its first difference threshold value, which was determined by the aforementioned experiment. At the same time, the sucrose second difference threshold test samples concentrations were 115%, 120%, 125% and 130% of its compared sample concentration. The sucrose third to ninth difference threshold compared and test samples were prepared using the above analogy. The glucose, fructose, lactose and maltose first to ninth difference threshold were compared and test samples were prepared in the same manner as the sucrose samples. The universal sample concentrations of all the five natural sugars are listed in Supplementary Table 2.

Before the sensory analysis, all test samples were kept at 20 ^{o}C.

2.3. Sensory Panel

The sensory panel was of 18 experienced subjects (nine males and nine females, from 23 to 37 years old). All subjects were told the purpose of this study and trained for two weeks. They were asked not to smoke or eat for at least a half hour before each sensory evaluation.

2.4. Absolute Threshold Sensory Analysis

The absolute threshold sensory analysis was based on the triangle test method. The procedures for sucrose, glucose, fructose, lactose and maltose were the same. Taking sucrose as an example, the absolute threshold sensory analysis procedure was as follows.

Step 1. Five different concentrations of sucrose solutions were prepared as absolute threshold samples. Three random numbers were marked on each one of the three identical test cups. Sucrose absolute threshold sample 1 was taken as the test object and 20 mL of Sample 1 was poured at random into one or two of the three marked cups. Then, 20 mL of the compared sample (ultrapure water) were poured into the remaining two cups or one cup. The above three cups of samples comprised one test group. Eighteen same test groups were prepared and named as Test Round 1.

Step 2. The sucrose absolute threshold samples 2 to 5 were used as the test object, sequentially. Step 1 was repeated and Test Rounds 2 to 5 were prepared.

Step 3. The sensory panel was asked to sit in the sensory evaluation room. Each assessor sat in a separate seat and was given one test group in Test Round 1.

Step 4. Assessors were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 5. Each assessor was asked to take one cup of the test group and hold it in the mouth for 10 seconds and then expectorate. They were then instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 6. Each assessor was asked to repeat the Steps 4 and 5 to evaluate the remaining two cups of the test group. Then, each assessor was asked to write down the number of the sample that differed on the answer sheet (as shown in

Supplementary Figure 1).

Step 7. Each assessor was asked to repeat Steps 4– 6 to evaluate Test Rounds 2 to 5 and to write down the odd-one-out in each test round.

Step 8. The answers for each test round were checked. If the number of correct answers in a test round was less than 12, this test round's evaluation result was "wrong". If the number of correct answers was equal to or greater than 12, this test round's evaluation result was "right". Thus, five sets of evaluation results could be obtained.

Step 9. If Test Round *n*'s evaluation result was "wrong" and all of the subsequent test round evaluation results were "right", the sucrose absolute threshold value could be calculated according to the following equation:

$$C_{suc.atv} = \sqrt{C_{atvn} \times C_{atvn+1}} \tag{1}$$

Where C_{atvn} was the sample concentration of Test Round *n*, C_{atvn+1} was the sample concentration of the test round after round *n*.

2.5. Difference Threshold Sensory Analysis

The difference threshold sensory analysis was based on the paired comparison method. The procedures for sucrose, glucose, fructose, lactose and maltose were the same. Taking sucrose as an example, the difference threshold sensory analysis procedure was as follows.

Step 1. Three random numbers were marked on each one of the two identical test cups. Sucrose's first difference threshold sample 1 was the test object and 20 mL were poured into one cup at random. Then, 20 mL of the compared sample were poured into the other cup. The two cups made up one test group. Eighteen sets were prepared and named as Test Round 1.

Step 2. Sucrose first difference threshold samples 2 to 4 were used as the test object, sequentially. Step 1 was repeated and Test Rounds 2 to 4 were prepared.

Step 3. The sensory panel was asked to sit in the sensory evaluation room. Each assessor sat in a separate seat and was given one sample set for Test Round 1.

Step 4. Assessors were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 5. Each assessor was asked to take one cup of the test group and hold it in the mouth for 10 seconds and then expectorate. After it, they were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 6. Each assessor was asked to repeat Steps 4 and 5 to evaluate the other cup in the test group. Then, each assessor was asked to write down the sweeter sample's three-number code on the answer sheet (as shown in Supplementary Figure 2).

Step 7. Each assessor was asked to repeat Steps 4–6 to evaluate Test Rounds 2 to 4 and to write down the code of each test round's sweet sample.

Step 8. The result of each test round was checked. If one test round's number of correct answers was less than 13, this test round's evaluation result was "wrong". If the number was equal to or greater than 13, this test round's evaluation result was "right". Thus, evaluation results for four test rounds could be obtained.

Step 9. If Test Round *n*'s evaluation result was "wrong", and all the subsequent test rounds' evaluation results were "right", sucrose's first difference threshold value could be calculated according to the following equation:

$$C_{suc.dtv1} = \sqrt{C_{dtvn} \times C_{dtvn+1}} \quad (2)$$

Where C_{dtvn} was the sample concentration of Test Round *n*, C_{dtvn+1} was the sample concentration of the test round after round *n*.

Step 10. Taking sucrose's second to ninth difference threshold samples as test objects and repeating Steps 1 to 9 eight times, $C_{suc.dtv2}$ to $C_{suc.dtv9}$ of sucrose could be obtained.

2.6. Sensory sweetness and sweetness conversion

Prior to the single sugar and mixed sugar comparison experiments, the sweet sensory difference strength curve was plotted with absolute threshold value and nine difference threshold values for each sugar as the *X*-axis and the sensory difference strength as the *Y*-axis. The curve could be fitted into the logarithmic form and the Weber fraction of each sugar could be calculated. Using sucrose as an example and defining the absolute threshold as 1, the sweetness of sucrose at any concentration could be calculated through the curve.

The sweet sensory difference strength logarithm curve was plotted by taking the absolute threshold value of each sugar and logarithm of the nine difference threshold values as the *X*-axis and the sensory difference strength as the *Y*-axis. The curve could be fitted into the linear form and the concentration relationship between sucrose and any one of the four other sugars at the same sweetness, named as sweetness index (SI), could be calculated from the fitted lines. Using SI, the sweetness of the four other sugars could be converted based on the sweetness of sucrose.

2.7. Single sugar sweetness comparison

A single sugar comparison based on the paired comparison method was used to compare the accuracy of our novel sweetness measurement and conversion method with previous studies. Sucrose concentrations of 2%, 6%, and 10% were selected as the samples for low, middle and high concentrations in this comparison experiment, respectively. Two groups of glucose, fructose, lactose and maltose solutions were tested with one group named "novel group" with solution concentrations calculated using our novel method and the second group named "previous group" with solution concentrations calculated by a method used in previous studies (Carocho, Morales, & Ferreira, 2017; Chattopadhyay, Raychaudhuri, & Chakraborty, 2014; Grembecka, 2015; Sardesai & Waldshan, 1991). Each group included three concentrations for comparison with the three sucrose concentrations. All the 18 subjects were asked to evaluate as follows.

Step 1. Three random numbers were marked on each one of two identical test cups, and 20 mL of 2% sucrose solution were poured into one random cup. Then, 20 mL of the corresponding glucose test sample of the novel group were poured into the other cup. The above two cups made up one test group. Eighteen groups were prepared and named as Test Round 1.

Step 2. The corresponding fructose, lactose and maltose test samples were used as the test objects, respectively. Step 1 was repeated and Test Rounds 2 to 4 were prepared.

Step 3. The sensory panel was asked to sit in the sensory evaluation room. Each assessor sat in a separate seat and was given one test set from Test Round 1.

Step 4. Assessors were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 5. Each assessor was asked to take one cup of the test group and hold it in the mouth for 10 seconds and then expectorate. After it, they were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 6. Each assessor was asked to repeat Steps 4 and 5 to evaluate the other one cup in the test group. Then, each assessor was asked to write down the three-number code of the sweeter sample on the answer sheet (as shown in Supplementary figure 3).

Step 7. Samples of 6% and 10% sucrose were compared and their corresponding glucose, fructose, lactose, maltose test samples of novel group were used as the test objects. Repeating Steps 1 to 6, the novel group's evaluation results could be obtained.

Step 8. 2%, 6%, 10% sucrose compare samples and their corresponding glucose, fructose, lactose, maltose test samples of previous group were used as the test objects. Repeating Steps 1 to 7, the previous group's evaluation results could be obtained.

2.8. Mixed-Sugars Sweetness Comparison

A mixed sugars sweetness comparison based on paired comparison method was used to verify the accuracy of our novel conversion method. Sucrose solutions with sweetness of 6, 12 and 18 were selected as the samples for low, middle and high sweetness levels. Three mixed-sugars test groups were prepared and named as low group, middle group and high group. Each group included four kinds of mixed-sugars: sucrose + glucose, sucrose + glucose + fructose, sucrose + glucose + fructose + maltose and sucrose + glucose + fructose + lactose + maltose. The concentrations for all three mixed sugar groups were calculated by our novel conversion method (As shown in Table 4 of Supplementary Material). All 18 subjects were asked to evaluate as follows:.

Step 1. Three random numbers were marked on each of two identical test cups. Sweetness 6 sucrose solution (20 mL) was poured into one random cup, then 20 mL of the mixed sugars of the low sweetness group were poured into the other one. The above two cups made up one test group. Eighteen groups were prepared and named as Test Round 1.

Step 2. The 2nd to 4th mixed-sugars were used as the test objects, respectively. Then, Step 1 was repeated and Test Rounds 2 to 4 were prepared.

Step 3. The sensory panel was asked to sit in the sensory evaluation room. Each assessor sat in a separate seat and was given one test group of Test Round 1.

Step 4. Assessors were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 5. Each assessor was asked to take one cup of the test group and hold it in the mouth for 10 seconds and then expectorate. After it, they were instructed to rinse their mouths with 20 mL ultrapure water for 10 seconds and then expectorate.

Step 6. Each assessor was asked to repeat Steps 4 and 5 to evaluate the other cup in the test group. Then each assessor was asked to write down the sweeter sample's three-number code on the answer sheet (as shown in Supplementary Figure 4).

Step 7. Sweetness 12, and 16 sucrose samples were compared and the corresponding mixed-sugars of middle and high groups were taken as the test objects. Repeating Steps 1 to 6, the three group's evaluation results could be obtained.

3. Results and discussion

3.1. Absolute Threshold Sensory Analysis

The absolute threshold values of sucrose, glucose, fructose, lactose and maltose were 0.424%, 0.675%, 0.324%, 1.125% and 1.025%, respectively (Table 1). These results reflect the sweet intensity of the five natural sugars as follows: fructose > sucrose > glucose > maltose > lactose.

Table 1. Absolute Threshold Sensory Analysis Results of the Five Natural Sugars

Sugar	Correct option number of the sensory analysis					Absolute threshold value, %
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	
Sucrose	11	13[a]	15	18	18	0.424
Glucose	10	11	10	15[a]	16	0.675
Fructose	10	14[a]	18	18	17	0.324
Lactose	9	11	9	13[a]	15	1.125
Maltose	8	6	9	13[a]	17	1.025

[a] The test round's evaluation result before this round was wrong; this test round and all the following rounds' evaluation result were right.

3.2. Difference Threshold Sensory Analysis

The results of the difference thresholds analysis and Weber fraction are shown in Table 2. The accuracy of the different thresholds can be determined by the size of concentration interval for each sugar; the smaller the concentration interval between difference thresholds, the higher the accuracy of the results. The Weber fraction results of all five natural sugars were nearly the same, around 0.21, suggesting these results conformed to the Weber-Fechner Law, which means the ratio of difference threshold and original stimulus concentration is a constant. In a previous study that only tested sucrose and examined 5 different strength levels, the Weber fraction result for sucrose was 0.17 (H. G. Schutz & F. J. Pilgrim, 1957). Although the Weber fraction result was similar to that in our study, we think our results are more accurate, due to the fact five different sugars were tested and 9 different strength levels were examined.

Table 2. Difference Threshold Results and Weber Fraction of Five Natural Sugars

Difference threshold Number	Difference threshold value, %				
	Sucrose	Glucose	Fructose	Lactose	Maltose
1st	0.530	0.843	0.397	1.434	1.307
2nd	0.622	1.033	0.466	1.828	1.600
3rd	0.762	1.265	0.571	2.239	1.960
4th	0.933	1.549	0.671	2.742	2.400
5th	1.143	1.819	0.821	3.221	2.820
6th	1.343	2.137	0.965	3.784	3.313
7th	1.577	2.618	1.182	4.445	3.891
8th	1.932	3.075	1.447	5.222	4.766
9th	2.269	3.612	1.773	6.135	5.837
Weber fraction*	0.205±0.030	0.205±0.030	0.208±0.025	0.208±0.043	0.214±0.033
Total weber fraction			0.208±0.031		

* The weber fraction is the ratio of difference threshold and original stimulus concentration.

3.3. Sensory Sweetness and Sweetness conversion

Figure 1a shows the sweet sensory difference strength curves of sucrose, glucose, fructose, lactose and maltose. The five logarithmic form curves were the fitted curves of ten plots and were all fitted into the following equation form:

$$Sweet\ sensory\ difference\ strength = a \times log_{10}(C_{X-ose}) + b \quad (3)$$

Where C_{X-ose} was the concentration of each sugar.

The specific equation parameters of each sugar are listed in Table 3, which showed that all five fitted curves had a high R^2 (0.999, 0.997, 0.999, 0.991 and 0.997 for sucrose, glucose, fructose, lactose and maltose, respectively). This sweetness increase phenomenon and the form of fitted equation are closely in accordance with the Weber-Fechner Law (Masin, Zudini, & Antonelli, 2009; Norwich & Watson, 1998).

Based on the equation parameters of sucrose in Table 3 and defining the absolute threshold of sucrose sweetness as 1, the sweetness of sucrose at any concentration could be calculated through the curve according to the following equation:

$$S_{suc} = 12.36 \times log_{10}(C_{suc}) + 5.47 \quad (4)$$

Where C_{suc} was the concentration of sucrose.

Figure 1b shows the sweet sensory difference strength logarithm curves of sucrose, glucose, fructose, lactose and maltose. The five fitted lines of ten plots could fit into the following equation form:

$$Sweet\ sensory\ difference\ strength = a' \times L_{X-ose} + b' \quad (5)$$

Where L_{X-ose} was the logarithm value of sugar concentration.

The specific equation parameters of each sugar are listed in Table 3 and showed that sweet sensory difference strength had a strong linear relationship with the logarithm value of sugar concentration (0.999, 0.997, 0.999, 0.991 and 0.997 for sucrose, glucose, fructose, lactose and maltose, respectively).

Table 3. Equation Parameters of the Fitted Logarithm Curves and Fitted Lines (*S* is the sweet sensory difference strength)

Sugar	Fitted Curves				Fitted Lines					
	Fitted Equation	Equation parameters		R^2	Fitted Equation	Equation parameters				R^2
		a	b			a’	b’	StDev a’	*t*-test result of a’	
Sucrose		12.36	5.47	0.999		12.36	30.19	0.15	Compare value	0.999
Glucose		12.41	2.88	0.997		12.41	31.79	0.22	−0.56	0.997
Fructose	$S = a \times \log_{10}(C_{X\text{-}ose}) + b$	12.33	7.05	0.999	$S = a' \times L_{X\text{-}ose} + b'$	12.33	31.72	0.12	0.35	0.999
Lactose		12.37	-0.06	0.991		12.37	24.67	0.38	−0.09	0.991
Maltose		12.26	0.58	0.997		12.26	25.11	0.23	1.00	0.997

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In order to examine the relationship between concentration of sucrose and of the other four sugars at the same sweetness level, a *t*-test was used to verify the significance of fitted line slope for each sugar. The results showed that all the absolute values of glucose, fructose, lactose, and maltose were smaller than 2.12 (at the 95% confidence interval, Table 3), which indicates that the fitted lines of these four sugars and sucrose could be considered parallel to each other. This suggests the concentration logarithm ratios between sucrose and the four other sugars could be considered to be the same at the same sweetness. We named this ratio as sweetness index (SI), in which each average SI was the geometrical mean of the ratios from each of the ten plots. For sucrose, glucose, fructose, lactose and maltose, the SI was 1, 1.12, 0.94, 1.29 and 1.25, respectively.

Based on the SI, the concentration for sucrose and other sugars at the same sweetness could be converted according to the following equation:

$$C_{suc} = C_{X-ose}^{SI} \quad (6)$$

Where C_{suc} and C_{X-ose} were the concentrations of sucrose and another sugar; the SI was the exponent of C_{X-ose}.

Substituting Equation (6) into Equation (4), another sugar's sweetness at any concentration could be calculated according to the following equation:

$$S_{X-ose} = 12.36 \times log_{10}(C_{X-ose}^{SI}) + 5.47 \quad (7)$$

3.4. Single sugar's sweetness comparison experiment

Figures 2a–c show the 2%, 6% and 10% sucrose concentration comparison results, respectively with the experimental data listed in Supplemental Table 3. The previous study group is plotted on the left side of the *X*-axis and the group from this study plotted on the right side of the *X*-axis. The *Y*-axis indicates the sensory option number, which was obtained from the subject evaluation. The red line of each figure indicates the significant difference line, which is equal to 13. If the sensory option number was less than or equal to this line, then the test sample and the comparison sample were not significantly different from each other and their comparison result was marked as "correct". If the sensory option number was higher than this line, then their comparison result was marked as "wrong".

In the previous study group, the evaluation accuracy of low and middle level was only at 25%, whereas the accuracy of high level was at 50%, the total accuracy was 33.3% (as shown in Table 3 of Supplementary Material). The main reason for differences in evaluation accuracy might be as follows. In the previous sweetness and relative sweetness studies (Howard G. Schutz & Francis J. Pilgrim, 1957; Stone & Oliver, 1969), the sweetness–concentration curve was non-linear and the researchers chose a moderate level of sweetness, with sucrose concentrations at 2%, 3%, and 10% as the reference. The sweetness conversion method in these previous studies was based on specific concentration, which could not be varied if the reference concentration changed. For example, if the comparison concentration was not near the reference concentration, then the sweetness conversion method might not be very accurate or useful in application.

In this study, the sweetness index and sweetness conversion method were based on the logarithm curve, allowing the sweetness conversion to vary with changes in the reference concentration. As shown in Figure 2a–c and Table 3 of Supplementary Material, the sweetness conversion for three concentration levels had high percentage of accuracy (100%, 75% and 75%, respectively, total accuracy was 83.3%). Our results showed that the sweetness conversion method based on this study was suitable for a wider concentration range than the previous studies.

3.5. Mixed-Sugars' Sweetness Comparison Experiment

Figure 3a–c showed the sweetness 6, 12 and 18 levels' comparison experiments results, respectively, with the experimental data listed in Supplemental Table 4. The red line in each figure represents the significant difference line which is equal to 13. If the sensory option number was less than or equal to this line, the test sample and the comparison sample were not significantly different to each other and their comparison result was marked as "correct". If the sensory option number was higher than this line, then the comparison result was marked as "wrong". Results showed the evaluation accuracies of the low, middle and high sweetness groups were at 100%, indicating that for mixed-sugars, sweetness levels could be converted to each other with accurate applicability by the conversion method described in this study.

4. Conclusions

Instead of an “open-type” favored in previous studies, we used a “closed-type” question based on the triangle test method and the paired comparison test method to increase the evaluation stability of subjects in this study. Our results showed a more stable sensory sweetness definition and sweetness conversion method for sucrose, glucose, fructose, lactose and maltose. The results from single sugar and mixed-sugars sweetness comparisons demonstrated that our new sweetness definition and conversion method provided better sugar concentration ranges and accuracy than those previously reported. Hence, these novel calculations will establish more reliable sweetness indices and sweetness references for future sweet taste sensory applications, such as in the food industry, sweet taste sensors and electronic tongues.

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Figures

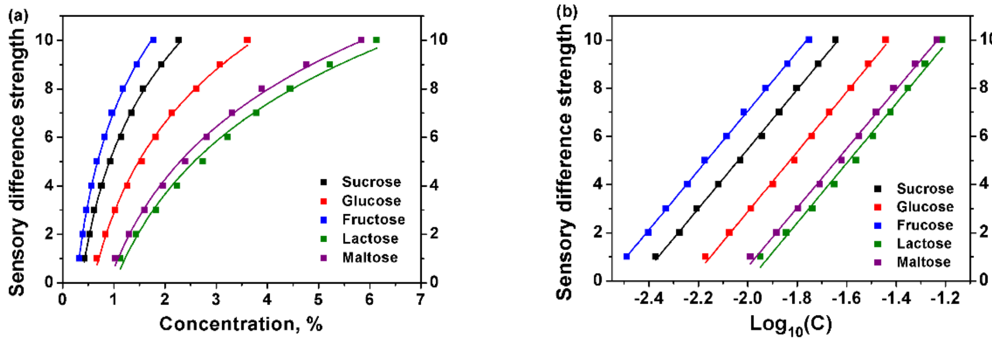

Figure 1. Sweet sensory difference strength curve (a) and its logarithm curve (b) of sucrose, glucose, fructose, lactose and maltose.

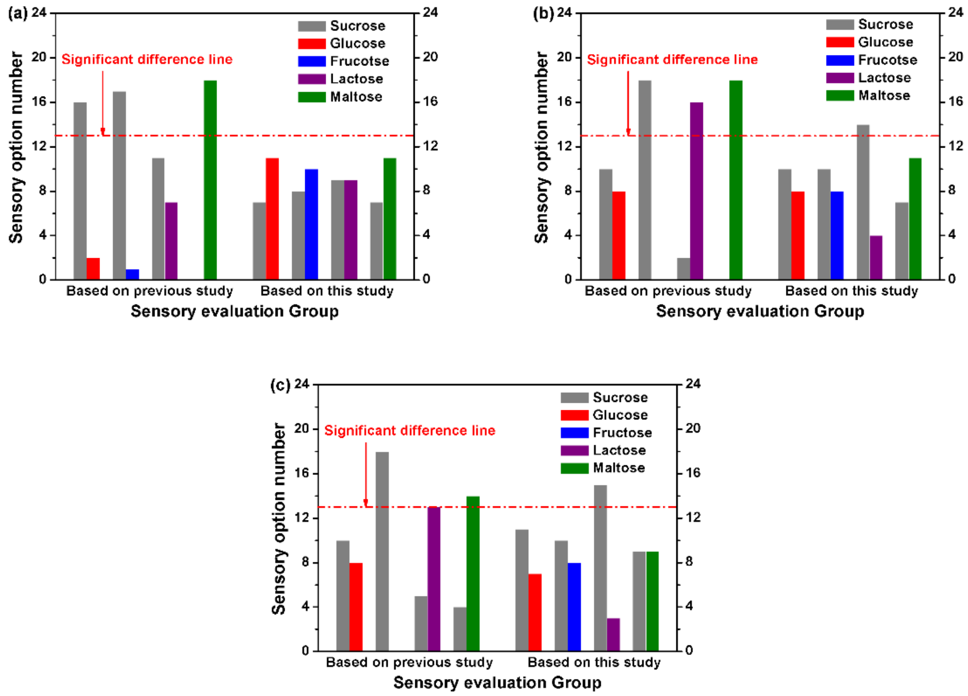

Figure 2. Single sweetener's sweetness comparison results: (a) 2% sucrose level comparison experiment; (b) 6% sucrose level comparison experiment; (c) 10% sucrose level comparison experiment.

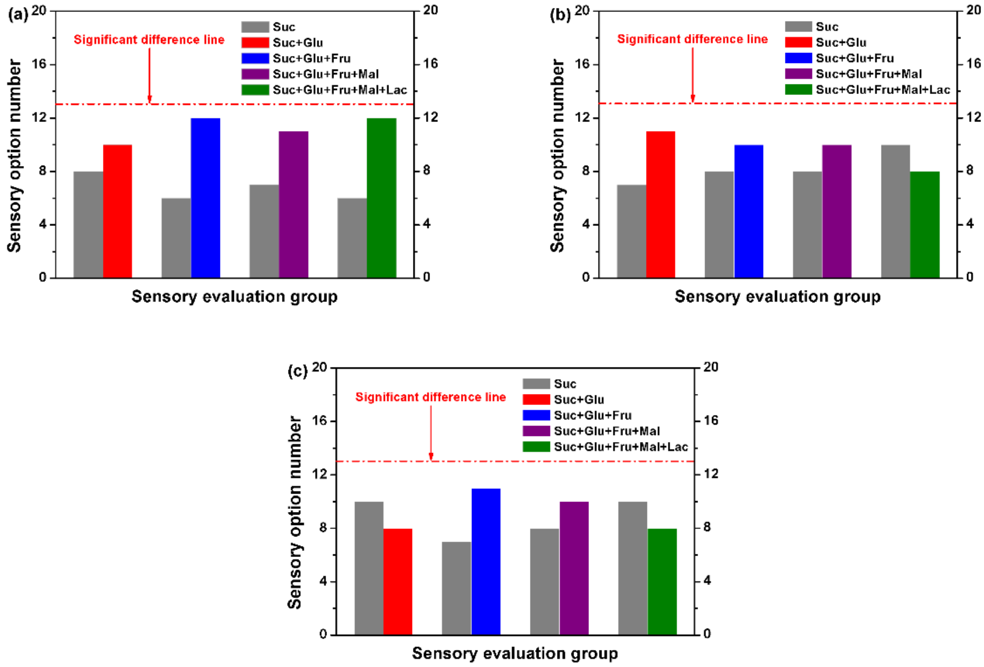

Figure 3. Mixed-sweeteners' sweetness comparison results: (a) sweetness 6 level comparison experiment; (b) sweetness 12 level comparison experiment; (c) sweetness 18 level comparison experiment.

Highlights

1. Sweetness calculation equation for sucrose established:

   $S_{suc}=12.36*\log_{10}(C_{suc})+5.47$.

2. Sweetness index (SI) for five sugars established.
3. Sweetness calculation equation for four sugars established:

   $S_{X\text{-}ose}=12.36*\log_{10}(C_{X\text{-}ose}^{SI})+5.47$.

4. Conversion method and equation are more reliable than those in previous studies.