beverages

MDPI

Article

Comparison of Temporal Profiles among Sucrose, Sucralose, and Acesulfame Potassium after Swallowing Sweetened Coffee Beverages and Sweetened Water Solutions

Naomi Gotow [1], Shinji Esumi [2], Hirofumi Kubota [2] and Tatsu Kobayakawa [1,*]

1 Human Informatics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba Central 6, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8566, Japan; nao-gotow@aist.go.jp
2 Products Research & Development Laboratory, Research & Development Headquarters, Asahi Soft Drink Co. Ltd., 1-1-21 Midori, Moriya, Ibaraki 302-0106, Japan; shinji.esumi@asahiinryo.co.jp (S.E.); hirofumi.kubota@asahiinryo.co.jp (H.K.)
* Correspondence: kobayakawa-tatsu@aist.go.jp; Tel.: +81-29-861-6730

Academic Editor: Manuel Malfeito Ferreira
Received: 5 December 2017; Accepted: 28 March 2018; Published: 2 April 2018

check for updates

Abstract: Non-nutritive sweeteners have been used as substitutes for nutritive sweeteners with the goal of preventing obesity and dental caries. The main factor responsible for the difference in taste between beverages containing a nutritive sweetener and those containing a non-nutritive sweetener is the temporal profile of sensory attributes. In this study, untrained panelists performed a time–intensity evaluation of sweetness, using one coffee beverage containing a nutritive sweetener (sucrose) and two coffee beverages containing non-nutritive sweeteners (sucralose or acesulfame potassium (acesulfame K)). They evaluated continuously perceived intensity of sweetness for 150 s after swallowing each coffee beverage. We did not detect a significant difference in temporal profiles among the three coffee beverages. To investigate why the temporal profiles of the three coffee beverages followed similar traces, all untrained participants who had participated in the coffee beverage session also performed a time–intensity evaluation of sweetness using three water solutions (sucrose-sweetened, sucralose-sweetened, and acesulfame K–sweetened deionized water). We observed a significant difference in temporal profiles among the three water solutions. These results indicate that differences in the temporal profiles of coffee beverages might be masked by factors other than the sweetness of the sweetener.

Keywords: temporal profile; time–intensity evaluation; sweetener; coffee beverage; water solution; untrained panelist

1. Introduction

Sucrose, a disaccharide, is one of the most common nutritive sweeteners used today, and provides metabolizable energy [1]. Overconsumption of sucrose causes chronic diseases such as obesity, metabolic syndrome leading to diabetes, and cardiovascular diseases [2]. In order to prevent these illnesses, non-nutritive sweeteners with very low or no calories have been used as substitutes for nutritive sweeteners [3,4].

Currently, the carbohydrate content of ordinary products such as coffee beverages is around 7.5 g per 100 mL [5] in Japan. In order to use the term “low-sugar”, it is necessary to decrease the carbohydrate content to less than 2.5 g per 100 mL of beverage [6], or to reduce the carbohydrate content by more than 2.5 g per 100 mL relative to the content in ordinary products [5]. In the European

Union, a "low-sugar" product has been defined as one that contains less than 5 g of sugar per 100 g for solids or 2.5 g of sugar per 100 mL for liquids [7]. The United States Food and Drug Administration has not defined the term "low-sugar" [8]. Non-nutritive sweeteners such as sucralose and acesulfame potassium (acesulfame K) are mainly used to enhance the sweetness of "low-sugar" products that contain fewer carbohydrates than conventional products. Per unit mass, sucralose and acesulfame K are several hundred times sweeter than sucrose [9,10].

The temporal profile of sensory attributes is the factor most responsible for a taste difference between a product sweetened with sucrose and one sweetened with a non-nutritive sweetener [11]. The temporal profiles of currently used non-nutritive sweeteners are not consistent with that of sucrose [12]. When investigating the temporal profiles of sensory attributes (i.e., sweetness) of water solutions and beverages, the measurement method used most frequently is a time–intensity evaluation [13,14]. This method records how the perceived intensity of sensory attributes changes over time [15]. To compare the temporal profiles of sweetness among multiple sweeteners, time–intensity evaluations are performed using water solutions [16–20] or foods (i.e., espresso coffee [21], chocolate milk [22], mixed fruit jam [23], milk chocolate [24], and snacks [25]). Melo and colleagues [26,27] sought to develop diabetic chocolate perceptually similar to ordinary chocolate in terms of its temporal profile. Trained panelists performed a time–intensity evaluation of sweetness using ordinary chocolate containing sucrose, as well as diabetic chocolates containing sucralose or stevioside. Their results revealed that the temporal profiles of sweetness were similar between ordinary and diabetic chocolates. Thus, time–intensity evaluation is considered to be a useful method for developing new products with temporal profiles that are as similar as possible to those of ordinary products.

The purpose of this study was to investigate whether the temporal profiles of sweetness differed between an ordinary coffee beverage containing nutritive sweetener (sucrose) and low-sugar coffee beverages containing non-nutritive sweeteners (sucralose or acesulfame K). Participants also performed a time–intensity evaluation of sweetness using sucrose-sweetened, sucralose-sweetened, and acesulfame K–sweetened water solutions as control samples. Gotow and colleagues [28] developed a time–intensity evaluation system for untrained panelists, which was used in this study.

2. Materials and Methods

2.1. Participants

This study was conducted in accordance with the revised version of the Declaration of Helsinki. All procedures in this study were approved by the ethical committee for ergonomic experiments of the National Institute of Advanced Industrial Science and Technology, Japan. Informed written consent was acquired from all participants. Ninety-four volunteers (39 female and 55 male) between the ages of 20 and 29 years (mean age $\pm$ standard deviation = 22.29 $\pm$ 1.90 years) participated in the experiments; volunteers contacted us after seeing our recruitment announcement on a website for the local community.

2.2. Materials

The experiments used eight types of non-released canned samples (Asahi Soft Drink, Tokyo, Japan): four sweetened coffee beverages and four sweetened water solutions. Sucrose, sucralose, and acesulfame K were used as sweeteners for the test trials, and stevia was used as the sweetener for the exercise trial.

Sucralose, acesulfame K, and stevia are 600, 200, and 350 times sweeter per unit mass than sucrose, respectively; here, the sweetness of sucrose was defined as 1 [9,10,29]. Most low-sugar canned coffee beverages available in Japan contain milk and have sweetness levels of 40–55. Therefore, we prepared a coffee beverage with milk that had a sweetness level of 50. More specifically, we calculated the concentrations satisfying the following equation: [sample concentration (g/L)] $\times$ [sweetness equivalence ratio of each sweetener, relative to sucrose] = 50. Accordingly, we prepared samples sweetened with 5% sucrose, 8.33×10^{-3}% sucralose, 2.50×10^{-2}% acesulfame K, and 14.28×10^{-3}% stevia.

For coffee beverages, we extracted components from 56.5 g of coffee beans (a blend of several medium-dark roasted Arabica beans), ground to a specified size, with deionized water at approximately 95 °C; added sweetener and 120 g of milk (3.6% fat, sterilization at 130 °C, Ohayo Dairy Products, Okayama, Japan) to the coffee extract; and then diluted the mixture in a measuring cylinder to 1 L with deionized water. After canning, each sample was subjected to retort sterilization. For water solutions, we canned deionized water containing each sweetener, and then performed retort sterilization. The canning process was completed using industrial equipment at the Asahi Soft Drink Co. Ltd.

We opened each package of canned sample, salt-free cracker ("Levain Classical non-salt topping", Yamazaki-Biscuits, Tokyo, Japan), and mineral water ("Asahi oishii mizu Fujisan", Asahi Soft Drink, Tokyo, Japan) 1 h before the start of the experiment. The salt-free cracker and mineral water were used to clean the participant's oral cavity [30,31]. A coffee sample or water solution (10 mL) was measured using a macropipette and poured into a paper cup (capacity 90 mL, Part Number SM-90-3, Tokan Kogyo, Tokyo, Japan). We poured one type of sample into each cup. In the interest of food sanitation and aroma retention, we covered the paper cup with a lid (Part Number SM-205-F, Tokan Kogyo), which was removed immediately before the sample was presented to the participants. The salt-free cracker was cut to a size of 2 cm × 2 cm, and one piece of cracker was served in a paper candy cup. Mineral water (10 mL) was measured using a macropipette and poured into a paper cup (capacity 90 mL, Part Number SM-90-3, Tokan Kogyo). Coffee beverages, water solutions, and mineral water were presented at room temperature (approximately 24 °C).

2.3. Time–Intensity Evaluation System

An outline of the time–intensity evaluation system is shown in Figure 1. The structure of this system was detailed by Gotow and colleagues [28,32]. However, to improve the portability of this system, we changed how the voltage output from the load cell was processed. More specifically, after the output voltage was amplified, it was subjected to an analog-to-digital (A/D) conversion at a frequency of 1 kHz on a microprocessor (Part Number Arduino Uno SMD Rev3, Arduino S.r.l., Ivrea, Italy). Average voltage was calculated in time windows of 50 milliseconds, and output to a personal computer via a serial port as a digital value corresponding to a six-point magnitude scale of perceived intensity.

2.4. Procedure

Time–intensity evaluation was performed by one participant at a time in a small room (width 165 cm × depth 275 cm × height 240 cm) shielded from outside noise. The door of the room was closed during measurement. A video camera and intercom were placed inside the room so that the experimenter could monitor and communicate with participants from outside the room. An air cleaner located inside the room was operated continuously to prevent odor retention.

The order of coffee beverage and water solution sessions was alternated between participants. To ensure the reliability and stability of the time–intensity evaluation [33,34], we presented a sample containing stevia in the first trial of each session, which was considered as a training trial. The presentation order of samples containing sucrose, sucralose, or acesulfame K in each session was counterbalanced among participants. The participant rested for approximately 7 min between trials in each session, as well as between the first and second sessions.

All instructions were displayed on the liquid crystal display (LCD) monitor placed in front of the participant. In the first trial of the first session, the participant performed the evaluation according to instructions displayed on the screen, while receiving oral instructions from experimenter. On the first screen of sequential trials, we instructed the participant to evaluate the continuously perceived intensity of sweetness on the tongue after swallowing the samples. On the same screen, based on previous studies [35,36] in which participants reported which part of their anatomy they used to perceived specific sensory attributes (e.g., some participants replied that they perceived vanilla aroma in their mouth), we instructed the participant regarding the part of the anatomy to which they should direct their attention (i.e., "on the tongue"), using an illustration of the sagittal plane of the head with the name of the part labeled (a display is shown in Figure 1). Next, the participant placed a cracker into their mouth to clean the oral cavity and continued masticating it for 15 s before the screen was switched. The participant swallowed the cracker remaining in their oral cavity, and then held 10 mL of mineral water in their mouth. After they transferred the water into the oral cavity, they swallowed it. The participant took 5 mL of sample in their mouth, which they held without swallowing, and then placed the index finger of their right hand into the ring of the time–intensity evaluation system. A countdown was displayed three seconds before the screen showed visual feedback about perceived intensity. The participant swallowed the sample in their mouth at the same time that the countdown reached 0 s and started the time–intensity evaluation of sweetness.

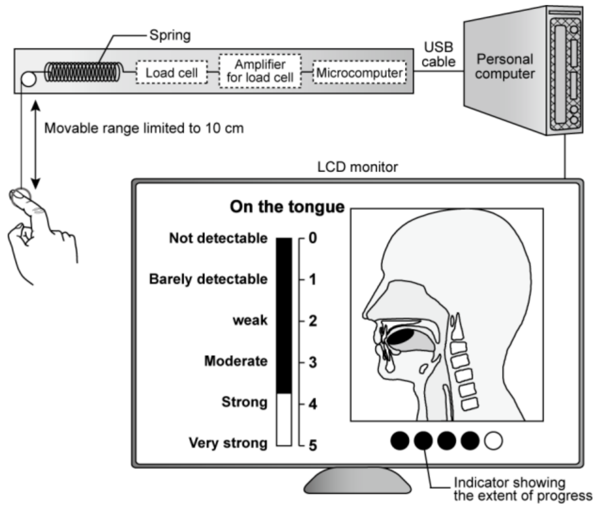

Figure 1. Outline of the time–intensity evaluation system. Participants evaluated perceived intensity by operating a pull-ring, which was a component of the evaluation system. The movable range of the ring was limited to 10 cm by a stopper. Positional information of the ring, synonymous with spring tension, was measured by a load cell, with output expressed as voltage. After the output voltage was amplified, it was subjected to analog-to-digital (A/D) conversion on a microprocessor at a frequency of 1 kHz. Average voltage was calculated in time windows of 50 milliseconds, and then output to a personal computer via a serial port as a digital value corresponding to a six-point magnitude scale of perceived intensity. To provide visual feedback in real time, the value of perceived intensity was displayed on a liquid crystal display (LCD) monitor as a black bar on a six-point magnitude scale (0: "not detectable" to 5: "very strong"). Furthermore, to inform the participant of the time remaining in the evaluation, an indicator of the extent of progress was shown on the screen.

For each sample, participants evaluated perceived intensity over 150 s. We instructed each participant to express the perceived intensity of sweetness by freely operating the pull-ring component of the evaluation system. Participants were not told the length of the evaluation time (i.e., how long they were to evaluate perceived intensity). Instead, to inform the participant of the time remaining in each trial, the screen displayed an indicator showing the extent of progress.

2.5. Analysis

In this study, we regarded the time when the screen was switched to visual feedback of perceived intensity as the starting point of the time–intensity evaluation (i.e., 0 s). We divided the evaluation period from 0 s to 150 s into 75 windows of 2 s each, and calculated the average perceived intensity in each time window. We conducted statistical analysis using these average values.

To investigate whether temporal profiles of sweetness differed among the three types of samples (sucrose-sweetened, sucrose-sweetened, and acesulfame K–sweetened samples), two-way repeated measures analysis of variance (ANOVA) for each solvent session (coffee beverage and water solution sessions) was performed for average values of perceived intensity, with sweetener and time as within-subject factors. Simple effects tests were conducted based on the significance of results obtained with ANOVA. Additionally, when temporal profiles of sweetness did not differ among three types of coffee beverages, we performed two-way repeated measures ANOVA for each sweetener for the average values of perceived intensity, with solvent session and time as within-subject factors.

We used IBM SPSS Statistics 23 (IBM Japan, Tokyo, Japan) for statistical analysis, and considered p values less than 0.05 as statistically significant.

3. Results

3.1. Comparison of Temporal Profiles of Sweetness among Samples in Each Solvent Session

3.1.1. Sweetened Coffee Beverage

The temporal profiles of sweetness of each sweetened coffee beverage are shown in Figure 2. Two-way repeated measures ANOVA revealed a significant main effect of time (F [74, 6882] = 326.78, $p < 0.001$).

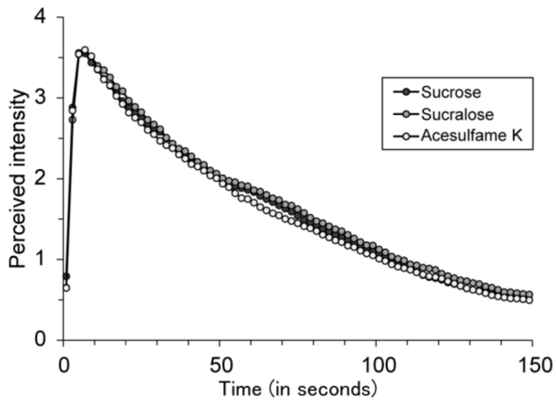

Figure 2. Temporal profiles of sweetness of each sweetened coffee beverage. Temporal profiles of sweetness were obtained for 150 s after participants swallowed sweetened coffee beverages.

3.1.2. Sweetener in Water Solution

The temporal profiles of sweetness of each sweetener in water solution are shown in Figure 3. Two-way repeated measures ANOVA revealed significant main effects of sweetener (F [2, 186] = 10.81, $p < 0.001$) and time (F [74, 6882] = 304.68, $p < 0.001$), and a significant interaction between sweetener and time (F [148, 13764) = 4.74, $p < 0.001$). The results of simple effects tests for interaction revealed significant simple main effects of sweetener in 74 time windows (medians of each time window = 3–149 s), and significant simple main effects of time for all sweeteners ($p < 0.05$). Multiple comparisons of the significant simple main effects of sweetener in those time windows, performed using the Ryan method, revealed significant differences between sucrose and sucralose in 63 time windows (medians = 25–149 s), between sucrose and acesulfame K in 25 time windows (medians = 3–15 s, 71–77 s, and 81–107 s), and between sucralose and acesulfame K in 40 time windows (medians = 3–81 s) ($p < 0.05$; for further details, see in Table 1). These results indicated that in some time windows, the perceived intensity of sweetness was significantly higher for sucralose-sweetened water solution than for sucrose-sweetened water solution, for acesulfame K–sweetened water solution than for sucrose-sweetened water solution, for sucrose-sweetened water solution than for acesulfame K–sweetened water solution, or for sucralose-sweetened water solution than for acesulfame K–sweetened water solution.

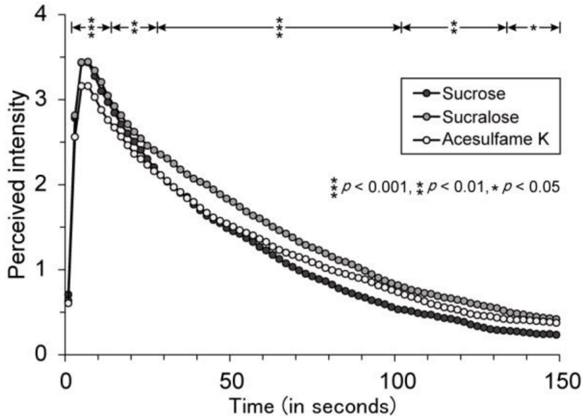

Figure 3. Temporal profiles of sweetness of each sweetener in water solution. Temporal profiles of sweetness were obtained for 150 s after participants swallowed sweetened water solutions.

Table 1. Results of sweetener in water solution: multiple comparisons for the significant simple main effects of sweetener in 74 time windows.

Time (s)	Sucrose	Sucralose	Acesulfame K	Time (s)	Sucrose	Sucralose	Acesulfame K
3	2.78 [a]	2.81 [a]	2.56 [b]	77	0.89 [a]	1.23 [b]	1.06 [c]
5	3.43 [a]	3.44 [a]	3.16 [b]	79	0.86 [a]	1.19 [b]	1.02 [a]
7	3.44 [a]	3.45 [a]	3.16 [b]	81	0.82 [a]	1.15 [b]	0.99 [c]
9	3.28 [a]	3.34 [a]	3.03 [b]	83	0.78 [a]	1.11 [b]	0.97 [b]
11	3.10 [a]	3.21 [a]	2.88 [b]	85	0.75 [a]	1.09 [b]	0.95 [b]
13	2.97 [a]	3.05 [a]	2.76 [b]	87	0.72 [a]	1.06 [b]	0.93 [b]
15	2.85 [a]	2.92 [a]	2.67 [b]	89	0.69 [a]	1.02 [b]	0.90 [b]
17	2.71 [a,b]	2.81 [a]	2.56 [b]	91	0.67 [a]	0.99 [b]	0.89 [b]
19	2.60 [a,b]	2.71 [a]	2.46 [b]	93	0.64 [a]	0.95 [b]	0.85 [b]
21	2.51 [a,b]	2.62 [a]	2.36 [b]	95	0.62 [a]	0.90 [b]	0.81 [b]
23	2.41 [a,b]	2.54 [a]	2.30 [b]	97	0.59 [a]	0.87 [b]	0.79 [b]
25	2.30 [a]	2.46 [b]	2.23 [a]	99	0.56 [a]	0.84 [b]	0.76 [b]
27	2.20 [a]	2.41 [b]	2.16 [a]	101	0.53 [a]	0.82 [b]	0.74 [b]
29	2.11 [a]	2.35 [b]	2.11 [a]	103	0.53 [a]	0.79 [b]	0.71 [b]
31	2.04 [a]	2.31 [b]	2.04 [a]	105	0.51 [a]	0.76 [b]	0.68 [b]
33	1.97 [a]	2.25 [b]	1.97 [a]	107	0.49 [a]	0.75 [b]	0.66 [b]
35	1.90 [a]	2.18 [b]	1.91 [a]	109	0.48 [a]	0.73 [b]	0.63 [a,b]
37	1.86 [a]	2.12 [b]	1.84 [a]	111	0.47 [a]	0.71 [b]	0.60 [a,b]
39	1.77 [a]	2.07 [b]	1.80 [a]	113	0.45 [a]	0.69 [b]	0.58 [a,b]
41	1.70 [a]	2.03 [b]	1.73 [a]	115	0.43 [a]	0.67 [b]	0.56 [a,b]
43	1.63 [a]	2.00 [b]	1.67 [a]	117	0.42 [a]	0.66 [b]	0.54 [a,b]
45	1.59 [a]	1.94 [b]	1.61 [a]	119	0.41 [a]	0.65 [b]	0.53 [a,b]
47	1.55 [a]	1.89 [b]	1.57 [a]	121	0.39 [a]	0.63 [b]	0.50 [a,b]
49	1.49 [a]	1.84 [b]	1.54 [a]	123	0.36 [a]	0.61 [b]	0.48 [a,b]
51	1.45 [a]	1.80 [b]	1.51 [a]	125	0.34 [a]	0.59 [b]	0.47 [a,b]
53	1.42 [a]	1.74 [b]	1.46 [a]	127	0.32 [a]	0.57 [b]	0.46 [a,b]
55	1.37 [a]	1.68 [b]	1.43 [a]	129	0.30 [a]	0.56 [b]	0.45 [a,b]
57	1.33 [a]	1.64 [b]	1.40 [a]	131	0.29 [a]	0.55 [b]	0.44 [a,b]
59	1.27 [a]	1.60 [b]	1.36 [a]	133	0.28 [a]	0.52 [b]	0.42 [a,b]
61	1.23 [a]	1.56 [b]	1.33 [a]	135	0.28 [a]	0.49 [b]	0.41 [a,b]
63	1.17 [a]	1.51 [b]	1.27 [a]	137	0.27 [a]	0.48 [b]	0.41 [a,b]
65	1.12 [a]	1.46 [b]	1.23 [a]	139	0.26 [a]	0.47 [b]	0.41 [a,b]
67	1.07 [a]	1.42 [b]	1.20 [a]	141	0.26 [a]	0.46 [b]	0.40 [a,b]
69	1.03 [a]	1.38 [b]	1.17 [a]	143	0.25 [a]	0.45 [b]	0.40 [a,b]
71	0.99 [a]	1.33 [b]	1.15 [c]	145	0.24 [a]	0.44 [b]	0.39 [a,b]
73	0.95 [a]	1.29 [b]	1.12 [c]	147	0.24 [a]	0.43 [b]	0.38 [a,b]
75	0.92 [a]	1.26 [b]	1.09 [c]	149	0.23 [a]	0.42 [b]	0.37 [a,b]

Values for each time window are medians (e.g., 1 s means the time window from 0–2 s), and values for each sweetener are sweetness intensities. In each time window, values with same letters did not differ statistically, but values with different letters differed significantly with $p < 0.05$.

3.2. Comparison of Temporal Profiles between Solvent Sessions for Each Sweetener

3.2.1. Sucrose

Two-way repeated measures ANOVA revealed significant main effects of solvent session (F [1, 93] = 41.28, $p < 0.001$) and time (F [74, 6882] = 344.18, $p < 0.001$), and a significant interaction between solvent session and time (F [74, 6882] = 4.74, $p < 0.001$). The results of simple effects tests for interaction revealed significant simple main effects of solvent session in 70 time windows (medians of each time window = 11–149 s) and significant simple main effects of time in both solvent sessions ($p < 0.05$). These results indicated that in some time windows, the perceived intensity of sweetness was significantly higher for sucrose-sweetened coffee beverage than for sucrose-sweetened water solution.

3.2.2. Sucralose

Two-way repeated measures ANOVA revealed significant main effects of solvent session (F [1, 93] = 16.72, $p < 0.001$) and time (F [74, 6882] = 301.38, $p < 0.001$), and a significant interaction between solvent session and time (F [74, 6882] = 2.43, $p < 0.001$). The results of simple effects tests for interaction revealed significant simple main effects of solvent session in 64 time windows (medians of each time window = 9–129 s and 133–137 s) and significant simple main effects of time in both solvent sessions ($p < 0.05$). These results indicated that in some time windows, the perceived intensity of sweetness was significantly higher for sucralose-sweetened coffee beverage than for sucralose-sweetened water solution.

3.2.3. Acesulfame K

Two-way repeated measures ANOVA revealed significant main effects of solvent session (F [1, 93] = 36.17, $p < 0.001$) and time (F [74, 6882] = 300.36, $p < 0.001$), and a significant interaction between solvent session and time (F [74, 6882] = 4.48, $p < 0.001$). The results of simple effects tests for interaction revealed significant simple main effects of solvent session in 67 time windows (medians of each time window = 3–135 s) and significant simple main effects of time in both solvent sessions ($p < 0.05$). These results indicated that in some time windows, the perceived intensity of sweetness was significantly higher for acesulfame K–sweetened coffee beverage than for acesulfame K–sweetened water solution.

4. Discussion

4.1. Temporal Profiles of Sweetness of Sweetened Coffee Beverages

In this study, untrained panelists performed a time–intensity evaluation of sweetness using three coffee beverages and three water solutions. Temporal profiles of sweetness followed similar traces among all coffee beverages. To explain this result, we propose the following hypotheses. First, differences among sweeteners may have been masked by factors other than the sweetness of the sweeteners contained in the coffee beverages. This hypothesis would be supported by the observation of significant differences among sweeteners in the time–intensity evaluation of the sweetness of water solutions. Second, untrained panelists might be unable to perceive differences among sweeteners when performing a time–intensity evaluation of the sweetness of coffee beverages or water solutions. However, this second hypothesis was not supported because temporal profiles significantly differed among the water solutions, leaving the first hypothesis as a potential explanation. To further test the validity of the first hypothesis, for each sweetener we compared the temporal profiles of sweetness between a coffee beverage and a water solution. The results demonstrated that for all sweeteners, the temporal profile was significantly higher for the coffee beverage than for the water solution. In other words, factors other than the sweetness of a sweetener might affect the temporal profiles of sweetness of coffee beverages.

The following factors might affect the temporal profiles of sweetness of the coffee beverages. The first candidate is the sweetness of milk [37–39]. We hypothesized that the sweetness of the water solutions was derived only from sweetener, whereas the sweetness of the coffee beverages was derived from the addition of milk or the synergy between sweetener and milk. The second candidate is the aroma of milk [40–44]. We hypothesized that addition of milk caused a decrease in coffee-like aroma [45,46] and an increase in sweet aroma [47], thereby enhancing the sweetness. The third candidate is the "halo-damping effect" [48–50] of sensory attributes other than sweetness. When a participant performs psychophysical evaluation of a single sensory attribute per trial, the evaluation value might be biased by the effects of sensory attributes other than the one to which they were instructed to pay attention [13,14]. Therefore, we hypothesized that because participants performed a time–intensity evaluation of only sweetness in this study, the perceived intensity of sweetness increased due to the halo-damping effect. The fourth candidate is the novelty of the coffee beverages. We hypothesized that due to the use of unreleased products in this study, the novelty of the coffee beverages distracted the untrained panelists and prevent them from discriminating sweetness among sweeteners. The fifth candidate is the interactions between the sweetener and other ingredients. We hypothesized that such effects elicited a bitter taste. The sixth candidate is the viscosity of coffee beverages. Because coffee beverages are more viscous than water solutions, sweeteners contained in coffee beverages might bind more strongly to taste receptors, and might not be washed out as rapidly by the saliva. We hypothesized that this phenomenon might enhance lingering sweetness. The seventh candidate is the natural sweetness of coffee. Some reducing sugars are present in roasted coffee, so that the water-soluble part of them may contribute to the overall flavor of the coffee [51]. We hypothesized that the sweetness of coffee beverages was derived from the addition of a sweetener or the synergy between sweetener and coffee.

To model the temporal profiles of sweetness of beverages containing non-nutritive sweeteners on the temporal profiles of sweetness of sucrose-sweetened beverages, multiple non-nutritive sweeteners are used in combination [52]. Specially, sucralose and acesulfame K have been combined in many low-calorie foods and beverages to achieve a temporal profile of sweetness similar to that of sucrose [53–55]. Based on this trend, in the near future, we intend to employ a time–intensity evaluation of sweetness with untrained panelists using coffee beverages containing combinations of sucralose and acesulfame K.

4.2. Temporal Profiles of Sweetness of Sweeteners in Water Solutions

As controls in this study, we used three types of water solutions. The temporal profiles of sweetness significantly differed among these water solutions. This result was inconsistent with the results of some studies reporting that the duration of sweetness does not differ among sucrose, sucralose, and acesulfame K [17,18], and another study reporting that the duration of sweetness was longer for sucrose than for sucrose and acesulfame K [56]. The temporal profiles of sweetness of various sweeteners vary with concentration [57], and perceived intensities of sensory attributes differ among untrained and trained panelists [58,59]. These factors might explain why results differed between this and previous studies.

5. Conclusions

In this study, we investigated whether the temporal profiles of sweetness differed between an ordinary coffee beverage containing a nutritive sweetener and low-sugar coffee beverages containing non-nutritive sweeteners. A time–intensity evaluation of sweetness revealed that temporal profiles followed similar traces among sucrose-, sucralose-, and acesulfame K–sweetened coffee beverages. In other words, the result indicated that the sensory attributes of low-sugar products (coffee beverages containing non-nutritive sweeteners) are close to those of ordinary products (coffee beverage containing sucrose), at least from the viewpoint of lingering sweetness.

Additionally, to investigate why temporal profiles of sweetness did not differ among the three coffee beverages, the untrained panelists performed a time–intensity evaluation of sweetness using three water solutions (sucrose-sweetened, sucralose-sweetened, and acesulfame K–sweetened deionized water) as control samples. We observed significant differences among the temporal profiles of the three water solutions, suggesting that differences in the temporal profiles of the three sweetened coffee beverages were masked by factors other than the sweetness of the sweeteners. Because this study was performed using untrained panelists, who represent the end users of released beverages, the results may provide information useful for beverage development.

Acknowledgments: This study was mainly funded by Asahi Soft Drink Co., Ltd., which had no control over the interpretation, writing, or publication of this work. This study was also partially supported by JSPS KAKENHI Grant Numbers 26245073 and 16K04418.

Author Contributions: Naomi Gotow participated in the study design and coordination, performed the statistical analysis, and drafted the manuscript; Shinji Esumi and Hirofumi Kubota conceived of the study and participated in its design; Tatsu Kobayakawa, who is the corresponding author, conceived of the study, participated in its design and coordination, undertook most of the revisions, and supervised the drafting of the manuscript.

Conflicts of Interest: This study was mainly funded by Asahi Soft Drink Co., Ltd.; this sponsor had no control over the interpretation, writing, or publication of this work.

References

1. White, J.S. Sucrose, HFCS, and fructose: History, manufacture, composition, applications, and production. In *Fructose, High Fructose Corn Syrup, Sucrose and Health*; Rippe, J.M., Ed.; Humana Press: New York, NY, USA, 2014; pp. 13–33.
2. Clemens, R.A.; Jones, J.M.; Kern, M.; Lee, S.-Y.; Mayhew, E.J.; Slavin, J.L.; Zivanovic, S. Functionality of sugars in foods and health. *Compr. Rev. Food Sci. Food Saf.* **2016**, *15*, 433–470. [CrossRef]
3. Gardner, C.; Wylie-Rosett, J.; Gidding, S.S.; Steffen, L.M.; Johnson, R.K.; Reader, D.; Lichtenstein, A.H.; on Behalf of the American Heart Association Nutrition Committee of the Council on Nutrition, Physical Activity and Metabolism, Council on Arteriosclerosis, Thrombosis and Vascular Biology, Council on Cardiovascular Disease in the Young, & the American Diabetes Association. Nonnutritive sweeteners: Current use and health perspectives: A scientific statement from the American Heart Association and the American Diabetes Association. *Diabetes Care* **2012**, *35*, 1798–1808. [PubMed]
4. Roberts, M.W.; Wright, J.T. Nonnutritive, low caloric substitutes for food sugars: Clinical implications for addressing the incidence of dental caries and overweight/obesity. *Int. J. Denti.* **2012**, *2012*, 625701. [CrossRef] [PubMed]
5. Japan Soft Drink Association. Question and Answer about Soft Drinks: Please Tell me the Difference between "Low Sugar" and "Non-Sugar" Coffee Beverages. Available online: http://www.j-sda.or.jp/ippan/qa_view.php?id=55&cat=1 (accessed on 5 December 2017).
6. Ministry of Health, Labor and Welfare. In *Nutrition Labelling Standards*. Available online: http://www.caa.go.jp/foods/pdf/syokuhin344.pdf (accessed on 5 December 2017).
7. European Union. Regulation (EC) No. 1924/2006 of the European Parliament and of the Council of 20 December 2006 on nutrition and health claims made on foods. *Off. J. Eur. Union* **2006**, *49*, L404/9.
8. Institute of Medicine (US) Committee on Examination of Front-of-Package Nutrition Rating Systems and Symbols. Appendix B FDA regulatory requirements for nutrient content claims. In *Front-of-Package Nutrition Rating Systems and Symbols*; Wartella, E.A., Lichtenstein, A.H., Caitlin, S., Boon, C.S., Eds.; National Academies Press: Washington, DC, USA, 2010.
9. Insel, P.M.; Turner, R.E.; Ross, D. Carbohydrates: Simple sugars and complex chains. In *Discovering Nutrition*, 3rd ed.; Jones and Bartlett Publishers: Sudbury, MA, USA, 2010; pp. 135–167.
10. Tharp, B.W.; Young, L.S. High-intensity sweeteners. In *Tharp & Young on Ice Cream: An Encyclopedic Guide to Ice Cream Science and Technology*; DEStech Publications: Pennsylvania, PA, USA, 2013; pp. 176–177.
11. DuBois, G.E. Saccharin and cyclamate. In *Sweeteners and Sugar Alternatives in Food Technology*; Mitchell, H., Ed.; Blackwell Publishing: Oxford, UK, 2006; pp. 103–129.
12. Di Monaco, R.; Miele, N.A.; Volpe, S.; Picone, D.; Cavella, S. Temporal sweetness profile of MNEI and comparison with commercial sweeteners. *J. Sens. Stud.* **2014**, *29*, 385–394. [CrossRef]

13. Meillon, S.; Urbano, C.; Schlich, P. Contribution of the temporal dominance of sensations (TDS) method to the sensory description of subtle differences in partially dealcoholized red wines. *Food Qual. Prefer.* **2009**, *20*, 490–499. [CrossRef]
14. Pineau, N.; Schlich, P.; Cordelle, S.; Mathonnière, C.; Issanchou, S.; Imbert, A.; Rogeaux, M.; Etiévant, P.; Köster, E. Temporal dominance of sensations: Construction of the TDS curves and comparison with time–intensity. *Food Qual. Prefer.* **2009**, *20*, 450–455. [CrossRef]
15. Lee, W.E., III; Pangborn, M. Time–intensity: The temporal aspects of sensory perception. *Food Technol.* **1986**, *40*, 71–78, 82.
16. Ayya, N.; Lawless, H.T. Potency of sweetness of aspartame, d-tryptophan and thaumatin evaluated by single value and time–intensity measurements. *Chem. Senses* **1992**, *17*, 245–259. [CrossRef]
17. Duizer, L.M.; Bloom, K.; Findlay, C.J. The effect of line orientation on the recording of time–intensity perception of sweetener solutions. *Food Qual. Prefer.* **1995**, *6*, 121–126. [CrossRef]
18. Ketelsen, S.M.; Keay, C.L.; Wiet, S.G. Time–intensity parameters of selected carbohydrate and high potency sweeteners. *J. Food Sci.* **1993**, *58*, 1418–1421. [CrossRef]
19. Ott, D.B.; Ledwards, C.; Palmer, S.J. Perceived taste intensity and duration of nutritive and non-nutritive sweeteners in water using time–intensity (T-I) evaluations. *J. Food Sci.* **1991**, *56*, 535–542. [CrossRef]
20. Galmarini, M.V.; Zamora, M.C.; Chirife, J. Gustatory reaction time and time intensity measurements of trehalose and sucrose solutions and their mixtures. *J. Sens. Stud.* **2009**, *24*, 166–181. [CrossRef]
21. Azevedo, B.M.; Schmidt, F.L.; Bolini, H.M.A. High-intensity sweeteners in espresso coffee: Ideal and equivalent sweetness and time–intensity analysis. *Int. J. Food Sci. Technol.* **2015**, *50*, 1374–1381. [CrossRef]
22. Rodrigues, J.B.; Paixão, J.A.; Cruz, A.G.; Bolini, H.M.A. Chocolate milk with chia oil: Ideal sweetness, sweeteners equivalence, and dynamic sensory evaluation using a time–intensity methodology. *J. Food Sci.* **2015**, *80*, S2944–S2949. [CrossRef] [PubMed]
23. De Souza, V.R.; Pereira, P.A.P.; Pinheiro, A.C.M.; Bolini, H.M.A.; Borges, S.V.; Queiroz, F. Analysis of various sweeteners in low-sugar mixed fruit jam: Equivalent sweetness, time–intensity analysis and acceptance test. *Int. J. Food Sci. Technol.* **2013**, *48*, 1541–1548. [CrossRef]
24. Palazzo, A.B.; Carvalho, M.A.R.; Efraim, P.; Bolini, H.M.A. The determination of isosweetness concentrations of sucralose, rebaudioside and neotame as sucrose substitutes in new diet chocolate formulations using the time–intensity analysis. *J. Sens. Stud.* **2011**, *26*, 291–297. [CrossRef]
25. Patil, S.; Ravi, R.; Saraswathi, G.; Prakash, M. Development of low calorie snack food based on intense sweeteners. *J. Food Sci. Technol.* **2014**, *51*, 4096–4101. [CrossRef] [PubMed]
26. De Melo, L.L.M.M.; Bolini, H.M.A.; Efraim, P. Equisweet milk chocolates with intense sweeteners using time–intensity method. *J. Food Qual.* **2007**, *30*, 1056–1067. [CrossRef]
27. Melo, L.; Bolini, H.M.A.; Efraim, P. Low-calorie chocolates and acceptability/sensory properties. In *Chocolate in Health and Nutrition*; Watson, R., Preedy, V.R., Zibadi, S., Eds.; Humana Press: New York, NY, USA, 2013; pp. 163–176.
28. Gotow, N.; Moritani, A.; Hayakawa, Y.; Akutagawa, A.; Hashimoto, H.; Kobayakawa, T. Development of a time–intensity evaluation system for consumers: Measuring bitterness and retronasal aroma of coffee beverages in 106 untrained panelists. *J. Food Sci.* **2015**, *80*, S1343–S1351. [CrossRef] [PubMed]
29. Japan Soft Drink Association. Question and Answer about Soft Drinks: Stevia. Available online: http://www.j-sda.or.jp/sp/qa_view.php?id=118&cat=8 (accessed on 5 December 2017).
30. Green, B.G.; Lim, J.; Osterhoff, F.; Blacher, K.; Nachtigal, D. Taste mixture interactions: Suppression, additivity, and the predominance of sweetness. *Physiol. Behav.* **2010**, *101*, 731–737. [CrossRef] [PubMed]
31. Lawless, H.T.; Schlake, S.; Smythe, J.; Lim, J.; Yang, H.; Chapman, K.; Bolton, B. Metallic taste and retronasal smell. *Chem. Senses* **2004**, *29*, 25–33. [CrossRef] [PubMed]
32. Gotow, N.; Moritani, A.; Hayakawa, Y.; Akutagawa, A.; Hashimoto, H.; Kobayakawa, T. High consumption increases sensitivity to after-flavor of canned coffee beverages. *Food Qual. Prefer.* **2015**, *44*, 162–171. [CrossRef]
33. Lawless, H.L.; Heymann, H. Context effects and biases in sensory judgement. In *Sensory Evaluation of Food: Principles and Practices*, 2nd ed.; Springer: New York, NY, USA, 2010; pp. 203–225.
34. Plemmons, L.E.; Resurreccion, A.V.A. A warm-up sample improves reliability of responses in descriptive analysis. *J. Sens. Stud.* **1998**, *13*, 359–376. [CrossRef]
35. Lim, J.; Johnson, M.B. Potential mechanisms of retronasal odor referral to the mouth. *Chem. Senses* **2011**, *36*, 283–289. [CrossRef] [PubMed]

36. Lim, J.; Johnson, M.B. The role of congruency in retronasal odor referral to the mouth. *Chem. Senses* **2012**, *37*, 515–522. [CrossRef] [PubMed]
37. Chapman, K.W.; Lawless, H.T.; Boor, K.J. Quantitative descriptive analysis and principal component analysis for sensory characterization of ultrapasteurized milk. *J. Dairy Sci.* **2001**, *84*, 12–20. [CrossRef]
38. Heymann, H.; Lawless, H.T. Context effects and biases in sensory judgment. In *Sensory Evaluation of Food: Principles and Practices*; Springer Science+Business Media: New York, NY, USA, 1999; pp. 301–340.
39. Lee, G.H.; Lee, J.S.; Shin, M.G. Sensory attribute comparison of consumer milk using descriptive analysis. *Food Sci. Biotechnol.* **2003**, *12*, 480–484.
40. Frank, R.A.; Byram, J. Taste–smell interactions are tastant and odorant dependent. *Chem. Senses* **1988**, *13*, 445–455. [CrossRef]
41. Frank, R.A.; Ducheny, K.; Mize, S.J.S. Strawberry odor, but not red color, enhances the sweetness of sucrose solutions. *Chem. Senses* **1989**, *14*, 371–377. [CrossRef]
42. Labbe, D.; Damevin, L.; Vaccher, C.; Morgenegg, C.; Martin, N. Modulation of perceived taste by olfaction in familiar and unfamiliar beverages. *Food Qual. Prefer.* **2006**, *17*, 582–589. [CrossRef]
43. Schifferstein, H.N.; Verlegh, P.W. The role of congruency and pleasantness in odor-induced taste enhancement. *Acta Psychol.* **1996**, *94*, 87–105. [CrossRef]
44. Stevenson, R.J.; Prescott, J.; Boakes, R.A. Confusing tastes and smells: How odours can influence the perception of sweet and sour tastes. *Chem. Senses* **1999**, *24*, 627–635. [CrossRef] [PubMed]
45. Bücking, M.; Steinhart, H. Headspace GC and sensory analysis characterization of the influence of different milk additives on the flavor release of coffee beverages. *J. Agric. Food Chem.* **2002**, *50*, 1529–1534. [CrossRef] [PubMed]
46. Itobe, T.; Nishimura, O.; Kumazawa, K. Influence of milk on aroma release and aroma perception during consumption of coffee beverages. *Food Sci. Technol. Res.* **2015**, *21*, 607–614. [CrossRef]
47. Liu, J.; Liu, M.; He, C.; Song, H.; Guo, J.; Wang, Y.; Yang, H.; Su, X. A comparative study of aroma-active compounds between dark and milk chocolate: Relationship to sensory perception. *J. Sci. Food Agric.* **2015**, *95*, 1362–1372. [CrossRef] [PubMed]
48. Clark, C.C.; Lawless, H.T. Limiting response alternatives in time–intensity scaling: An examination of the halo-dumping effect. *Chem. Senses* **1994**, *19*, 583–594. [CrossRef] [PubMed]
49. Prescott, J. Flavour as a psychological construct: Implications for perceiving and measuring the sensory qualities of foods. *Food Qual. Prefer.* **1999**, *10*, 349–356. [CrossRef]
50. Prescott, J.; Johnstone, V.; Francis, J. Odor-taste interactions: Effects of attentional strategies during exposure. *Chem. Senses* **2004**, *29*, 331–340. [CrossRef] [PubMed]
51. Heath, H.B. The Physiology of Flavour: Taste and Aroma Perception. In *Coffee: Volume 3, Physiology*; Clarke, R.J., Macrae, R., Eds.; Elsevier Applied Science Publisher: Essex, UK, 1988; pp. 141–170.
52. Bakal, A.I. Mixed Sweetener Functionality. In *Alternative Sweeteners*, 3rd ed.; Revised and Expand; O'Brien-Nabors, L., Ed.; Marcel Dekker, Inc.: New York, NY, USA, 2001; pp. 463–480.
53. Kemp, S.E.; Lindley, M.G. Developments in sweeteners for functional and speciality beverages. In *Functional and Speciality Beverage Technology*; Paquin, P., Ed.; Woodhead Publishing Limited: Cambridge, UK, 2009; pp. 39–54.
54. Kim, P. Sweetness sense. Sweeteners: Customizing Sweetness Profiles. In *Food Product Design*; Deis, R.C., Ed.; Virgo Publishing: Phoenix, AZ, USA, 2006; Volume 15, Number 11; p. 1.
55. Karstadt, M.L. Testing needed for acesulfame potassium, an artificial sweetener. *Environ. Health Perspect.* **2006**, *114*, A516. [CrossRef] [PubMed]
56. Goldsmith, L.A.; Merkel, C.M. Sucralose. In *Alternative Sweeteners*, 3rd ed.; Revised and Expand; O'Brien-Nabors, L., Ed.; Marcel Dekker, Inc.: New York, NY, USA, 2001; pp. 185–207.
57. Mahindru, S.N. High intensity-low calorie sweeteners. In *Food Additives: Characteristics, Detection and Estimation*; APH Publishing Corporation: New Delhi, India, 2008; pp. 53–104.

58. Losó, V.; Gere, A.; Györey, A.; Kókai, Z.; Sipos, L. Comparison of the performance of a trained and an untrained panel on sweetcorn varieties with the panelcheck software. *APSTRACT* **2012**, *1–2*, 77–83.
59. Roberts, A.K.; Vickers, Z.M. A comparison of trained and untrained judges' evaluation of sensory attribute intensities and liking of cheddar cheeses. *J. Sens. Stud.* **1994**, *9*, 1–20. [CrossRef]