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Temporal check-all-that-apply on the sensory profiling of sucrose-replaced sweetener blends of natural and synthetic origin

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Abstract

The present study aimed to formulate sucrose-replaced samples with natural or synthetic sweeteners, and to benchmark the temporal sensory profile of sucrose-replaced samples to a control sample (100% sucrose). Acesulfame-K, aspartame, erythritol, rebaudioside M, and sucralose replaced sucrose at four different levels (25%, 50%, 75%, and 100%) in aqueous solutions. A trained sensory panel evaluated the samples with temporal check-all-that-apply. The sweeteners showed great individual differences in their ability to replace sucrose. Except for aspartame, the 25% sucrose replacement across all sweeteners was not significantly different from the control. Aspartame, erythritol, and sucralose showed no difference from sucrose for the 50% and 75% sucrose-replaced samples. In contrast, a replacement of above 25% sucrose with acesulfame-K and rebaudioside M resulted in significant variations in the aftertaste period resulting in bitter off-taste and licorice off-flavor, respectively, compared to the control. Conclusively, synthetic and natural sweeteners were able to partially replace sucrose without altering the temporal sensory profile.

Practical Applications

This study showed high variability of achievable sucrose replacement suggesting that the choice of sweetener is crucial for a successful replacement. Blends of sucralose or erythritol with sucrose was most suitable to mimic the sensory profile of sucrose. This can be applied by the food industry in the innovation of low energy food and beverage products with comparable sensory profiles to the sucrose counterparts.

1 | INTRODUCTION

The global obesity epidemic continues to increase concomitantly with its health-related impacts (Collaborators et al., 2017). Comprehensive research has shown a significant effect of sugar-sweetened beverage consumption on the intake of free sugars, weight gain, and high prevalence of non-communicable diseases (NCDs) (Bechthold et al., 2019; Vartanian et al., 2007). To negate the unhealthy weight gain and related NCDs, the World Health Organization is currently recommending a reduction of sugar intake to less than 10% of the daily energy intake, whereas a further reduction to less than 5% is planned in the future (WHO, 2015).

To replace the reduced sweetness of sugar-reduced food products the more prevalent strategies are addition of non-nutritive sweeteners, multisensory integration, and food structure modification (Hutchings et al., 2019; Wang, Mielby, Junge, et al., 2019). Sweetness enhancement has been shown through cross-modal interaction effects by incorporation of aromas and colors and through food structure modification by homogeneously distribution of sugar in the food product. However, these strategies only allow a small reduction in sugar content (Bertelsen et al., 2021; Mosca et al., 2010; Wang, Mielby, Thybo, et al., 2019). The most effective and applied strategy in the food industry is the application of non-nutritive sweeteners. Non-nutritive sweeteners are primarily high-potency sweeteners, allowing for minimal usage amounts and thus a negligible energy contribution to achieve the same sweetness potency compared to sugars. Nevertheless, despite a long history of sweetener use and development of improved formulas in the food industry, consumers are still more likely to consume products with sugars (IFIC, 2021) and prefer sugar-sweetened products over their fully sugar-replaced counterparts (Markey et al., 2015). Moreover, complete substitution of sugar with non-nutritive sweeteners in food and beverages might significantly alter the brain reward system compared to the sugar-containing counterparts (Frank et al., 2008), suggesting a crucial role of the detection of sugars (Spector & Schier, 2018).

Sucrose and high-fructose corn syrups account for the majority of sugar sweeteners used in beverages, especially soft drinks (Mohan Rao & Ramalakshmi, 2011). The widespread usage of sucrose in beverage applications is related to its sensory profile being characterized by a rapid onset and quick decay of sweet taste without undesirable side-tastes and off-flavors (DuBois & Prakash, 2012). These properties make sucrose the "golden standard" of sugars and the reference benchmark in numerous sensory studies examining sensory properties of non-nutritive sweeteners (Ayya & Lawless, 1992; Hanger et al., 1996; Heikel et al., 2012; Jang et al., 2021; Portmann & Kilcast, 1998; Tan et al., 2019; Wiet & Beyts, 1992).

Commercially relevant non-nutritive sweeteners are associated with side-tastes, off-flavors, and lingering sensations. These include initial bitter taste and lingering sensations of sweet and bitter tastes together with descriptors such as chemical, licorice, and metallic (Mora & Dando, 2021). According to DuBois and Prakash (2012), discovering a sweetener that successfully matches the sensory properties of sucrose is likely to be a non-achievable goal.

Earlier studies have shown that non-nutritive bulk and high-potency sweetener blends (Portmann & Kilcast, 1998) as well as multiple high-potency sweetener blends (Hanger et al., 1996) have a sensory profile similar to that of sucrose. Specifically, when comparing the sensory properties of single intense sweeteners to blends, Hanger et al. (1996) found that blends were perceived as having reduced off-flavors and lingering sweet aftertaste. Likewise, Portmann and Kilcast (1998) found that blends of bulk sweeteners (sucrose or maltitol) and high-potency sweeteners (acesulfame-K or cyclamate) exhibited significantly lower intensities of bitter and licorice flavor and aftertaste when compared to non-blended high-potency sweeteners, thus achieving a profile similar to sucrose.

Temporal sensory methods make it possible to capture these distinctive lingering sensations and aftertaste attributes associated with sweeteners. Methods such as time–intensity and temporal dominance of sensations (TDS) have been used to evaluate the profiles of individual sweeteners and blends in both aqueous and model matrices (Ketelsen et al., 1993; Kim et al., 2015; Ott et al., 1991; Portmann & Kilcast, 1996; Tian et al., 2022; Wu et al., 2019) as well as in complex food matrices such as chocolates (Palazzo et al., 2011), whey beverages (Parker et al., 2018), and fruit beverages (Sousa Lima et al., 2021; Zorn et al., 2014). However, these methodologies only allow a single or few dominant attributes to be evaluated at a time, limiting the characterization of the temporal profile of sweeteners, which are usually accompanied by a variety of tastes and flavors, besides sweetness. To overcome this limitation, a novel temporal method, temporal check-all-that-apply (TCATA) (Castura et al., 2016), which allows for the evaluation of multiple attributes simultaneously, has recently been applied in the evaluation of single sweeteners in aqueous solutions (Reyes et al., 2017; Tan et al., 2019), a lemonade model (Wu et al., 2019), and whey beverages (Harwood & Drake, 2021; Parker et al., 2018).

The current study compared potential non-nutritive sweeteners in blends with sucrose as means to reduce the sugar content of beverages while maintaining the "golden standard" sucrose-like temporal sensory profile. Within these frames, samples with increased levels of sugar replacement achieved by combining sucrose and the appropriate sweetener concentration to achieve the same level of sweetness were formulated and subsequently compared to a full sucrose sample. The non-nutritive synthetic sweeteners acesulfame-K, aspartame, and sucralose and the non-nutritive natural sweeteners erythritol and rebaudioside used in this study were selected based on their abundance in new product launches in the years 2018–2020, as reported by Innova Market Insight (Green, 2021). Synthetic sweeteners were defined as those not occurring in nature, whereas natural sweeteners were considered natural due to their natural occurrence (Mora & Dando, 2021). The specific aims of this study were:

i. formulate sucrose-replaced samples with natural or synthetic sweeteners, and
ii. to benchmark the temporal sensory profile of sucrose-replaced samples to a sucrose control sample.

To our knowledge, this is the first paper to evaluate an incremental replacement of sucrose with notable sweeteners in aqueous solution using TCATA.

2 | MATERIALS AND METHODS

2.1 | Materials

The sweeteners used for preparing the aqueous solutions were sucrose (Nordic Sugar A/S, Copenhagen, Denmark), acesulfame-K, aspartame, erythritol, rebaudioside M 90%, and sucralose (Bulk™, Gunfleet, Colchester, UK). Rebaudioside M was provided by Nascent Health Sciences LLC (Iselin, New Jersey, USA), and acesulfame-K (ace-

K), aspartame, and erythritol were provided by EASIS A/S (Aarhus, Denmark). All samples were prepared as % (w/w) concentrations using tap water.

2.2 | Overview of sensory experiment

To ensure that the concentration of sweeteners added to the sucrose-replaced samples had an equivalent sweetness intensity to the replaced sucrose amount, sweetness concentration–response curves (CRC) were initially constructed for each of the sweeteners examined in this study. This was considered necessary, since the relative sweetness of sweeteners, especially intense sweeteners, is concentration dependent (DuBois et al., 1991). Thus, it is necessary to account for relative sweetness changes at different sucrose equivalent concentrations (SEC). Thereafter, sucrose-replaced samples at four increasing levels – 25%, 50%, 75%, and 100% replacement – were formulated and evaluated with TCATA (Castura et al., 2016). The replacement levels 100% replacement, 75% replacement, and 50% replacement complied with the EU regulation on the health-related nutrient claims for "energy-free" (max. 1 g of sucrose/100 mL), "low sugars" (max. 2.5 g of sucrose/100 mL), and "low energy" (max. 5 g of sucrose/100 mL), respectively (EU, 2007). The 25% replacement was added to have an intermediate replacement level between the 0% and 50% replacements.

2.2.1 | Trained panel and sample presentation

All sensory evaluations were conducted at the sensory facilities of the Food Science Department, Aarhus University, designed according to the ISO standards for sensory test rooms (ISO, 2007). A screened and trained sensory panel (ISO, 2012) of 8–10 assessors (aged 21–58 years, number per session is specified in Table 1) with experience in the sensory evaluation of sweet beverages was employed in all sensory evaluation sessions. The panel had received training regularly in all basic tastes, including the ones evaluated in the present study: sweet, bitter, sour, and astringent. To be a part of the panel assessors provided their consent and were informed that they could withdraw their consent and leave the study at any time.

One sweetener was evaluated per session and one session was conducted per day. The formulated samples used for constructing the CRCs and TCATA were evaluated in triplicate and presented in randomized order, according to a Williams Latin Square design. All samples were served at room temperature in 30-mL transparent plastic cups labeled with a three-digit blinding code. Between all evaluations, assessors were instructed to thoroughly cleanse their mouth and wait at least 100 s before evaluating the next sample. Still and carbonated water were provided as palate cleansers. Data was recorded with iPads using Compusense Cloud software (Compusense, Inc., Guelph, Ontario, Canada).

2.3 | Concentration–response curves

2.3.1 | Sample formulation

To formulate the samples for CRCs, the relative sweetness of the different sweeteners compared to a 5% sucrose solution was identified using a ranking procedure. This process was conducted separately for each of the sweeteners, and the trained panel received a 5% sucrose sample and five samples varying in sweetener concentration, which were thereafter ranked by sweetness intensity. The concentration of the sweetener closest to and not significantly different from the sucrose sample was used to calculate the relative sweetness of the individual sweeteners. If the sucrose sample was ranked between two concentrations of each of the individual sweeteners, a mean concentration of these was used to calculate the relative sweetness. Based on the relative sweetness, a range of sample concentrations corresponding to 2%, 4%, 5%, 7%, 8%, and 10% sucrose, respectively, were then formulated. A narrow concentration range reflecting the concentration levels used in the formulation of sucrose-replaced samples

TABLE 1 Concentrations of sucrose and sweeteners in percentage (%) in the control and sucrose-replaced samples.

		Sucrose replacement in percentage			
Sweetener session[a]	Control	25%	50%	75%	100%
Sucrose	8.5%	6.3%	4.3%	2.3%	–
Acesulfame-K	–	0.014%	0.030%	0.063%	0.133%
Sucrose	8.5%	6.3%	4.3%	2.3%	–
Aspartame	–	0.018%	0.029%	0.046%	0.074%
Sucrose	8.5%	6.0%	3.9%	1.9%	–
Erythritol	–	5.7%	8.5%	11.3%	14.0%
Sucrose	8.5%	6.3%	4.3%	2.3%	–
Rebaudioside M	–	0.013%	0.028%	0.059%	0.125%
Sucrose	8.5%	6.3%	4.3%	2.3%	–
Sucralose	–	0.005%	0.008%	0.013%	0.021%

[a]The number of assessors (females) in the sweetener session acesulfame-K, aspartame, erythritol, rebaudioside M, and sucralose were 8 (4), 10 (4), 10 (4), 9 (4), and 9 (4).

(Section 2.4) was used, as it has been shown to have improved the accuracy of the SEC of the sweeteners (Ko et al., 2020).

2.3.2 | Sensory evaluation by descriptive analysis

Generic descriptive analysis (DA) was conducted in separate sessions for the sample ranges of sucrose and each sweetener (Lawless & Heymann, 2010). In the vocabulary sessions, the sensory panel generated the attributes sweet taste, bitter taste, licorice flavor, floral honey flavor, caramel flavor, vanilla flavor, and cooling mouth feeling. The attributes found across all vocabulary sessions were combined and used in the individual sucrose and sweetener sessions. To train the panel in the generated flavor attributes, reference samples were provided. Thaumatin (Natex UK Limited, Letchworth Garden City, Hertfordshire, UK) at a 0.001% concentration in tap water was used as a licorice flavor reference. Caramel, vanilla, and honey aromas (Sosa, Barcelona, Spain) were provided as references for the attributes caramel flavor, vanilla flavor, and honey flavor descriptors, respectively. Attributes were evaluated on a 150-mm VAS line scale anchored with "very low" and "very high" at intensities 0 and 150 mm, respectively. Sucrose reference samples with 2%, 6%, and 10% sucrose anchored at 15, 75, and 135 mm, respectively. The assessors were instructed to taste all sucrose reference samples in the beginning of each session and could retaste these as needed throughout the session.

2.3.3 | Calculations

To model the CRC of the bulk sweeteners (sucrose and erythritol) and the high-potency sweeteners (acesulfame-K, aspartame, rebaudioside M, and sucralose), the mean sweet taste intensities were fitted with linear and logarithmic regression functions (Choi & Chung, 2014; Ko et al., 2020). The model fit R^2-values of sucrose, erythritol, acesulfame-K, aspartame, and rebaudioside M were 0.96, 0.99, 0.99, 0.98, and 0.99, respectively.

2.4 | Temporal check-all-that-apply

2.4.1 | Sample formulation

Sucrose-replaced samples were formulated at four increasing levels of replacement equivalent to an 8.5% sucrose concentration. Thus, the control sample without replacement contained 8.5% sucrose, whereas the 25%, 50%, 75%, and 100% replacement samples with high-potency sweeteners (acesulfame-K, aspartame, rebaudioside M, and sucralose) contained 6.3%, 4.3%, 2.3%, and 0% sucrose, respectively. Replacement concentrations of sweeteners were found by interpolation of the CRCs between sucrose and the sweetener of interest. The sucrose concentration in the erythritol replacement samples contained 6%, 3.9%, 1.9%, and 0% sucrose, respectively, to ensure that the EU caloric limit was not exceeded, since erythritol has a calorie contribution of 0.2 kcal/g. The concentrations applied in the sucrose-replaced samples made with different sweeteners are shown in Table 1. For each sweetener, a set of five samples, including a control sample with 8.5% sucrose and the four sucrose-replaced samples 25%, 50%, 75%, and 100%, were evaluated in a separate TCATA session.

2.4.2 | Temporal evaluation

TCATA fading (Ares et al., 2016) was used to evaluate the sucrose-replaced samples. Instead of the typical 8 s, a fading time of 5 s was chosen to improve temporal precision. Prior to the evaluation, the panel was familiarized with the TCATA method through training with commercial sweet beverages. A training session of 2 h was used to evaluate a passion fruit carbonated soda, a mixed berry squash, peach-flavored iced tea, and a sucrose-sweetened aqueous solution. The attributes generated during the DA vocabulary sessions (Section 2.3.2) used for the CRC construction were included in the TCATA evaluations and were: sweet, bitter, licorice, honey, caramel, vanilla, and cooling. After a panel discussion, the assessors agreed to add the attributes sour and astringent to the TCATA list. To evaluate the samples, the assessors were instructed to take a sip of the sample, press the start button, and immediately after that start to select the perceived attributes. After 7 s of in-mouth evaluation, the assessors were instructed to swallow the sample and continue selecting attributes. Each sample evaluation took a total of 60 s from the time the assessor pressed the start button.

2.4.3 | Statistical analyses

TCATA data sets consisted of binary measurements with 0 and 1 reflecting absence and presence of the attribute at each evaluation second, respectively. The data were segmented into equal-sized periods, attack (0–20 s), aftertaste (21–40 s), and finish (41–60 s) to allow for a mixed model analysis of variance (ANOVA)-based statistical approach that would take into account the individual differences of the assessors (Meyners & Hasted, 2021). In addition, time periods were applied to provide a perceptually relevant interpretation of the sweetener profile while preserving the temporal aspect (Visalli et al., 2020). In this study, the attack period refers to the build-up in-mouth and immediate sensation after swallowing, whereas the aftertaste period refers to the post-swallowing sensation. The finish period is related to the long-lasting lingering sensations associated with certain sweeteners.

Mean citation proportions were calculated for each attribute by summing counts of seconds (presence) within each period for every assessor and replicate divided by the period length in seconds (e.g., if an assessor selected an attribute for 9 s in a given period, the proportion was calculated as $9/20 = 0.45$).

Mean citation proportions for each attribute within each period were fitted as response variable using a linear mixed model (McMahon

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et al., 2017) with the "lmerTest" R package (Kuznetsova et al., 2017). The model used included sample as fixed effect, while assessor, replicate, and assessor interactions with replicate and sample were included as random effects. ANOVA was performed on the model to compute the sample effect on mean citation proportions. Dunnett's test from the "emmeans" R package (Lenth, 2022) was used to assess difference in mean citation proportions between the sucrose-replaced samples and the sucrose control. Analyses and visualization were conducted in R ver. 4.1.2 and RStudio ver. 2022.02.0. In all analyses, the statistical level of confidence was set at 95% ($p < .05$).

Temporal profiles were visualized with R package "tempR" (Castura, 2022) using citation proportions of each second (1–60 s) for each attribute within the samples. For visualization of each attribute curve a spline smoothing function was applied. For the sweet attribute the temporal summary parameters, time to peak sweetness citation (time until maximum sweetness) and peak sweetness citation proportion (citation proportion at maximum sweetness) were calculated.

3 | RESULTS

3.1 | Visualization of the temporal profiles and segmentation periods exemplified with rebaudioside M

To show the agreement between the temporal profiles and the chosen segmentation periods, the control sample and 75% replacement sample from the rebaudioside M session was used as an example. The temporal profiles from the individual sweetener sessions can be found in the supplementary materials (Figures S1–S5). The agreement between the temporal profile and segmentation periods was overall evident across all sweetener sessions.

Figure 1 presents the visualization of the temporal profile of the control and rebaudioside M 75% replacement sample overlaid with the segmentation by the attack, aftertaste, and finish periods. In both the control and rebaudioside M 75% replacement sample, the sweet attribute has high citation proportions in the attack and aftertaste periods compared to the other attributes. The sweet and vanilla attributes peak in the attack period of both samples, before gradually decreasing in the aftertaste and finish periods. Both samples show an astringency build-up in the attack and aftertaste periods, before peaking and then decreasing in the finish period of the control; it increases further in the finish period of the rebaudioside M 75% replacement sample. In the sucrose sample, caramel peaks in the attack period and gradually decreases in the aftertaste period with a further decrease in the finish period, whereas honey builds up in the attack period, peaks and decreases in the aftertaste period, before decreasing further in the finish period. In the 75% replacement sample licorice peaks in the attack period and gradually decreases in the aftertaste and finish periods, whereas bitter and caramel peak in the aftertaste period and decrease in the finish period. Citation proportions of sour and cooling throughout the temporal profiles are low (<0.2) for both samples. Similarly, low citation proportions (<0.2) are seen for bitter and licorice in the control

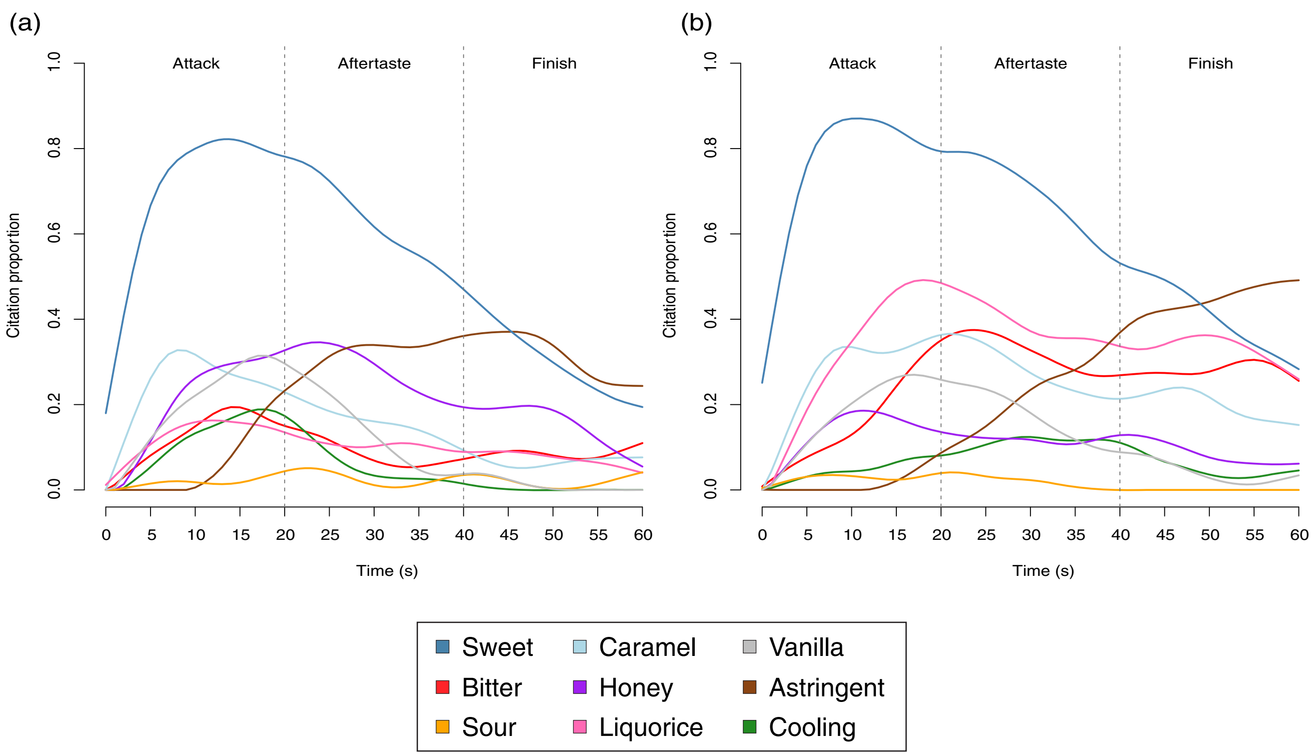

FIGURE 1 Temporal profiles presented with period segmentation of (a) control (sucrose) and (b) rebaudioside M (75% sucrose replacement). The vertical dotted lines represent the separation of periods. The box below the temporal profiles contains the attributes and their associated colors.

sample, whereas these are low for honey in the 75% replacement sample.

3.2 | Overview of sucrose replacement levels

Mean differences in citation proportions between the sucrose-replaced samples and the control (100% sucrose) in the periods attack (0–20 s), aftertaste (21–40 s), and finish (41–60 s) are presented in Table 2. Only attributes with a significant sample effect were included in the table (Table 2), whereas sweet taste is kept independent of its significance, since the evaluation of sweetness citation proportions is one of the main interests of the present study. As a result, sour and astringent were excluded. Tables S1–S3 with all attributes across all periods can be found in the supplementary materials.

No significant differences from the control were found for any of the sweeteners in 25% sucrose-replaced samples in the attack and aftertaste periods or for 50% sucrose-replaced samples in the attack period. However, differences in the attack period of the 75% sucrose-replaced samples and in the aftertaste and finish periods of the 50% and 75% sucrose-replaced samples were found for acesulfame-K and rebaudioside M. Consistently through all periods, differences in the 100% sucrose-replaced samples were seen for acesulfame-K, aspartame, and rebaudioside M. Overall, the temporal sensory profiles and associated variations were highly dependent on the sweetener.

Time to peak sweetness citation and peak sweetness citation proportions are presented in Table 3. Samples within the acesulfame-K, aspartame, and erythritol sessions showed similar time to peak sweetness citation lying between 4 and 5 s. In the rebaudioside M and sucralose sessions the onset showed larger differences varying from 4 to 6 s and 3 to 5 s, respectively. Sucralose samples with 50% and 100% sucrose replacement was the only samples found to have delayed time onset of >1 s when compared to the control sample. Peak sweetness citation proportion ranges for acesulfame-K, aspartame, erythritol, and rebaudioside M were 0.88–0.96, 0.87–0.93, 0.93–0.97, and 0.89–1.00, respectively, whereas for all samples in the sucralose session it was 1.00. A moderate difference (0.11) between the 100% sucrose-replaced rebaudioside M sample and the control was found, suggesting a difference in perceived maximum sweetness.

3.3 | Individual sweetener differences

A 50% replacement with acesulfame-K led to significant variations from the control in the aftertaste and finish periods for the attributes bitter and caramel (Table 2). Across all periods, a significant difference from the control was found for bitter in 75% replacement samples and for bitter and licorice in 100% replacement samples. Furthermore, the attribute honey was significantly different in the attack period of 75% and 100% replacement samples, respectively.

The 50% and 75% replacements with aspartame led to no significant variations from the control, whereas for the 25% replacement a significant difference was found for the vanilla attribute in the finish period. The 100% replacement with aspartame resulted in significant differences from the control across all periods for the bitter and licorice attributes.

Erythritol showed no significant variation from the control in any of the three periods in the 25%, 50%, and 75% sucrose-replaced samples. The only significant variation from the control was seen for the 100% sucrose-replace erythritol sample in the attributes bitterness, vanilla, and cooling in the aftertaste and finish periods of the 100% replacement sample.

Replacement of 25% with rebaudioside M was found not to vary significantly from the control in any of the periods examined. However, in the 50% replacement sample, the licorice and vanilla attributes were significantly different in the aftertaste and finish periods, respectively. The licorice attribute differed significantly from the control in all periods of the 75% and 100% replacements. Furthermore, the bitter attribute was found to differ significantly from the control in the attack period of the 100% replacement sample and in the attack and aftertaste periods of the 75% and 100% replacement samples.

No differences were found for any of the replacement samples with sucralose in the attack and finish periods. However, significant variation from the control was found for the attributes cooling and caramel flavor in the aftertaste period of the 75% and 100% replacement samples.

4 | DISCUSSION

4.1 | Applicability of periods in the temporal profiling of sweeteners

The segmentation of the temporal profile into the three periods attack, aftertaste, and finish seemed suitable and was in agreement with the temporal evolution of most attributes, except for those with very low citation proportions. For most attributes, there was a build-up and peak in intensity in-mouth and immediately after swallowing in the attack period, a gradual decrease of sensations in the aftertaste period, and a lingering of sensations in the finish period. Astringency did not follow this temporal evolution and showed to have an inverse temporal curve compared to other attributes, building up in the attack and aftertaste periods and peaking in the finish period, which is in agreement with previous studies (Reyes et al., 2017; Tan et al., 2019). Reyes et al. (2017) proposed that this might be explained by the high number of sample evaluations and in-between rinsing, leading to depletion of the salivary proteins responsible for lubrication and thus not associated with any of the sweeteners. Evaluation of multiple attributes in the aftertaste period is a common procedure in descriptive analyses of sweeteners. However, many of these results are difficult to compare, as the time of rating varies from 5 s to 1 min after expectoration (Fujimaru et al., 2012; Hanger et al., 1996; Jung et al., 2021; Wiet & Beyts, 1992). Thus, using periods in temporal profiling with TCATA simplifies the comparison to other types of evaluation methods, while conserving the temporal information (Dinnella et al., 2013; Nguyen et al., 2018). The use of periods also permits the

TABLE 2 Differences in mean citation proportions between sucrose-replaced samples and the control (sucrose) for the time intervals attack (0–20 s), aftertaste (21–40 s), and finish (41–60 s) together with ANOVA sample factor *p*-values presented for each attribute.

		Attack (0–20 s)				Aftertaste (21–40 s)					Finish (41–60 s)					
Sweetener session	Sucrose replacement	Sweet	Bitter	Lico.	Honey	Sweet	Bitter	Lico.	Caramel	Cooling	Sweet	Bitter	Lico.	Caramel	Vanilla	Cooling
Acesulfame-K	25%	0.00	+0.06	0.00	0.00	0.00	+0.06	+0.01	−0.07	0.00	−0.01	−0.02	+0.02	0.00	0.00	−0.10
	50%	−0.01	+0.19	+0.02	−0.13	+0.01	+0.30*	+0.06	+0.06	−0.02	+0.06	+0.11	+0.02	+0.11*	−0.02	−0.13
	75%	−0.05	+0.37***	+0.09	−0.21**	+0.03	+0.51***	+0.14	−0.06	−0.11	+0.03	+0.29*	+0.03	+0.04	−0.04	−0.10
	100%	−0.10	+0.48***	+0.21**	−0.21**	−0.03	+0.59***	+0.29**	−0.04	−0.05	+0.02	+0.42***	+0.15*	+0.01	−0.06	−0.11
	p	*.354*	*<.001*	*.002*	*<.001*	*.89*	*<.001*	*.011*	*.112*	*.684*	*.645*	*<.001*	*.045*	*.028*	*.824*	*.481*
Aspartame	25%	+0.01	+0.07	+0.06	0.00	+0.05	+0.02	0.00	−0.11	−0.05	+0.12	−0.01	+0.02	+0.01	+0.14**	+0.01
	50%	−0.03	+0.06	+0.07	+0.08	+0.02	+0.09	+0.12	−0.15	−0.02	−0.01	+0.11	+0.07	−0.08	+0.04	−0.02
	75%	−0.03	+0.13	+0.08	−0.02	+0.04	+0.15	+0.12	−0.02	−0.03	+0.08	+0.09	+0.09	+0.03	+0.04	−0.02
	100%	−0.05	+0.21***	+0.18**	−0.06	+0.02	+0.25*	+0.24***	−0.05	0.00	+0.09	+0.16*	+0.15**	−0.04	+0.01	+0.02
	p	*.31*	*.003*	*.013*	*.028*	*.903*	*.029*	*<.001*	*.208*	*.692*	*.03*	*.023*	*.013*	*.091*	*.006*	*.532*
Erythritol	25%	+0.04	0.00	−0.01	+0.01	+0.01	+0.04	+0.06	+0.06	+0.04	−0.02	−0.02	+0.06	+0.05	−0.06	+0.01
	50%	+0.03	−0.02	−0.09	−0.02	−0.03	+0.07	−0.06	+0.08	+0.15	+0.04	+0.06	−0.03	−0.02	−0.06	+0.12
	75%	+0.03	0.00	−0.02	−0.04	+0.07	−0.02	−0.01	+0.01	+0.11	+0.02	+0.02	−0.05	−0.03	−0.12	+0.13
	100%	0.00	+0.06	−0.07	+0.03	−0.05	0.21*	−0.02	−0.08	+0.17	−0.02	+0.05	−0.06	−0.06	−0.14*	+0.22*
	p	*.715*	*.829*	*.322*	*.735*	*.093*	*.018*	*.22*	*.341*	*.163*	*.698*	*.758*	*.05*	*.543*	*.049*	*.048*
Rebaudioside M	25%	+0.06	0.00	−0.02	+0.03	+0.10	+0.03	−0.02	+0.14	+0.08	+0.15	+0.08	+0.04	+0.07	+0.03	+0.04
	50%	+0.06	+0.08	+0.15	−0.03	+0.06	+0.21	+0.23*	+0.10	0.00	*+0.09*	+0.12	+0.11	+0.04	+0.10*	+0.03
	75%	+0.06	+0.04	+0.19*	−0.07	+0.06	+0.23*	+0.29**	+0.12	+0.06	+0.11	+0.20	+0.25*	+0.14	+0.03	+0.05
	100%	+0.08	+0.22**	+0.26**	−0.04	+0.04	+0.32**	+0.51***	+0.14	+0.06	+0.15	+0.28	+0.41***	+0.06	+0.03	+0.03
	p	*.231*	*.005*	*<.001*	*.332*	*.471*	*.003*	*<.001*	*.668*	*.522*	*.438*	*.052*	*<.001*	*.322*	*.079*	*.503*
Sucralose	25%	−0.04	+0.06	−0.02	0.00	+0.01	0.00	+0.05	+0.10	+0.04	+0.12	+0.02	+0.01	+0.05	−0.01	−0.06
	50%	+0.02	+0.03	−0.01	−0.11	+0.06	−0.01	+0.08	+0.05	−0.01	+0.10	−0.04	+0.05	+0.01	−0.04	−0.09
	75%	−0.01	−0.01	−0.02	−0.04	+0.03	+0.04	+0.11	+0.17*	+0.09	+0.12	+0.05	+0.08	+0.09	−0.04	−0.03
	100%	−0.05	+0.11	+0.10	−0.10	−0.06	+0.12	+0.17	+0.19**	+0.18*	+0.08	+0.19	+0.13	+0.12	−0.06	0.00
	p	*.435*	*.411*	*.221*	*.134*	*.045*	*.439*	*.14*	*.008*	*.016*	*.077*	*.062*	*.22*	*.059*	*.636*	*.219*

Note: – and + denotes a reduction and increase in the mean citation proportion of the attribute, respectively. Significant differences are based on a Dunnett's test indicated by *p < .05, **p < .01, and ***p < .001.
Abbreviation: Lico., licorice.

TABLE 3 Temporal summary parameters of sucrose-replaced samples and the control, time to peak sweetness citation and peak sweetness citation proportion.

Sweetener session	Sucrose replacement	Time to peak sweetness citation (s)	Peak sweetness citation proportion
Acesulfame-K	Control	5	0.96
	25%	5	0.92
	50%	5	0.96
	75%	5	0.88
	100%	5	0.96
Aspartame	Control	4	0.90
	25%	4	0.93
	50%	4	0.90
	75%	5	0.87
	100%	5	0.93
Erythritol	Control	4	0.93
	25%	5	0.97
	50%	5	0.93
	75%	5	0.97
	100%	4	0.93
Rebaudioside M	Control	5	0.89
	25%	6	0.96
	50%	4	0.93
	75%	5	0.96
	100%	4	1.00
Sucralose	Control	3	1.00
	25%	3	1.00
	50%	5	1.00
	75%	3	1.00
	100%	5	1.00

use of the mixed model ANOVA procedure by increasing the number of citations (Meyners & Hasted, 2021).

4.2 | Differences between the sucrose control and partial sucrose-replaced samples

The current study evaluated temporal sensory profiles of sucrose-replaced samples applying two naturally occurring and three synthetic sweeteners and benchmarked these to a full sucrose control sample. Partial sucrose replacement of up to 75% (equivalent to approx. 6% sucrose) with aspartame, erythritol, and sucralose did not elicit any sensory characteristics not associated with sucrose, thus achieving what can be considered a significant level of replacement. For acesulfame-K and rebaudioside M, only 25% replacement (equivalent to approx. 2% sucrose) was achieved in order to mimic the sucrose counterpart. For acesulfame-K, bitter and licorice characteristics arose at higher replacement levels. The sensory characteristics bitter taste and sensations of licorice and cooling were not associated with sucrose in the present study, whereas caramel, honey, and vanilla are considered sucrose-associated characteristics (Hutchings et al., 2019; Mora & Dando, 2021).

Examining aqueous solutions specifically, only one previous study has evaluated the temporal profile (Ayya & Lawless, 1992), and another the descriptive analysis profile of blends of sucrose and sweeteners (Jang et al., 2021). In agreement with our results, Ayya and Lawless (1992) found that blends with equal sweetness contributions (i.e., a 50% replacement sample) from sucrose and aspartame at low (5% SEC) and medium concentrations (10% SEC) had a bitterness intensity similar to sucrose only and lower than aspartame only within the first minute of evaluation; subsequently the bitterness differences between the blend samples and sucrose diminished. Jang et al. (2021) found that blends of sucrose and erythritol with rebaudiosides in ternary (rebaudioside A or D) blends produced sensory profiles with minimal off-flavors, off-tastes, and lingering effects comparable to a 10% sucrose control (Jang et al., 2021). Specifically, 60% sucrose replacement of an initial 10% sucrose (w/v) with a ternary blend of 4% sucrose, 3% SEC erythritol, and 3% SEC rebaudioside (either rebaudioside A or D) resulted in minimal off-flavors and off-tastes. In contrast, a blend without erythritol consisting of 4% sucrose, 3% SEC rebaudioside A, and 3% SEC rebaudioside D showed substantial off-flavors and off-tastes (Jang et al., 2021). Even though our study did not evaluate a ternary blend of sucrose, erythritol, and rebaudioside M, our binary blend results are similar to those of Jang et al. (2021); for rebaudioside M, a maximum of 25%, comparable to a SEC of 3% sucrose replacement, was achieved. Even though rebaudioside M and not rebaudioside D was applied in this study, both rebaudiosides are commercially relevant and have provided sensory characteristics and temporal profiles similar to those of sucrose (Prakash et al., 2014; Tian et al., 2022).

4.3 | Differences between the sucrose control and total sucrose-replaced samples

Similarly to the 100% sucrose-replaced samples used in this study, several studies have evaluated the temporal profile of sweeteners alone and compared these to sucrose (Ayya & Lawless, 1992; Gotow et al., 2018; Ketelsen et al., 1993; Kim et al., 2015; Ott et al., 1991; Reyes et al., 2017; Tan et al., 2019; Tian et al., 2022).

In our study, none of the sweeteners were able to fully mimic sucrose at 100% replacement without affecting the temporal profiles. This is in accordance with the results of previous studies using similar sweeteners (Ayya & Lawless, 1992; Reyes et al., 2017; Tan et al., 2019; Tian et al., 2022). Surprisingly, for all sweeteners investigated, no variations in sweet citation proportions were found between the sucrose-replaced samples and the control in any of the periods. This was unexpected, as previous studies applying temporal methods have reported lingering sweet taste for aspartame (Ketelsen et al., 1993; Ott et al., 1991; Portmann & Kilcast, 1996; Tan et al., 2019), sucralose (Tan et al., 2019), and rebaudioside M (Tian et al., 2022) when compared to sucrose. An explanation could be that all these studies, except for Tan et al. (2019), evaluated the sweeteners using time–intensity, a method that provides a precise measure of the intensity of one attribute at a time. Contrary, citation-based multi-attribute temporal methods such as TDS and TCATA rely on attribute selection frequencies to provide relative measures of intensity (Pineau et al., 2009). Thus, intensity-based temporal evaluation may better capture the lingering effects. The deviation of the present results from the TCATA results of Tan et al. (2019) might be explained by the difference in attribute fading time, as theirs was set to 10 s, whereas this study used 5 s. Consequently, a long fading time may extend the sensation of an attribute, resulting in overestimation of the duration (Rizo et al., 2020). Another explanation could be the use of higher concentrations of sucrose and thus SEC of the sweeteners in the previous studies compared to this study. Indeed, Ketelsen et al. (1993) investigated both high and low concentrations and found lingering sweetness of aspartame compared to sucrose only at 9% SEC and not at 5% SEC, whereas Ayya and Lawless (1992) did not find any differences across a range of concentrations. Contrary, Portmann and Kilcast (1996) found the sweetness profile of aspartame to be similar to sucrose at 10% SEC, but not at 5% SEC, where it had a pronounced lingering sensation. In agreement with this study, Kim et al. (2015) found no difference in the temporal sweetness of sucralose at a 5% SEC when compared to sucrose. Generally, these variations in sweetness lingering might be due to differences in the estimated potency and therefore the applied SEC of sweeteners, but also in profiling methods.

The lack of discrimination in astringency is in accordance with previous studies (Reyes et al., 2017; Tan et al., 2019). As explained above, this might be explained by the high number of sample evaluations and rinsing in between samples, leading to depletion of the salivary proteins responsible for lubrication and thus not associated with any of the sweeteners. Also, the sour attribute showed very low citations across all sweetener sessions and was not attributed to any sweetener, which then might have been an attribute of contrast between the samples and water.

4.4 | Individual sweetener characteristics

The time to peak sweetness was comparable across all sweetener sessions. This is in agreement with other studies applying TCATA (Reyes et al., 2017; Tan et al., 2019). However, these studies found times until peak sweetness >7 s, whereas the range found in this study was 3–6 s. This slight offset is likely caused by different TCATA procedures. This study selected attributes while having the sample in the mouth, whereas the other studies used a similar protocol, where attributes were selected after swallowing. Similar peak sweetness citation across the sweetener sessions indicated an overall comparable maximum sweetness intensity of the samples and validated the interpolated concentrations from the CRC's.

In accordance with the results obtained in the present study, other studies found acesulfame-K to be bitter tasting throughout the evaluation period (Ott et al., 1991; Tan et al., 2019), eliciting a significant bitterness (Schiffman et al., 1995) that becomes highly pronounced at concentrations above 5% SEC (DuBois & Prakash, 2012). In contrast to our findings, Reyes et al. (2017) did not find acesulfame-K to have a licorice taste. However, this might be explained by the lower concentration used in their study compared to the present study, their untrained consumer panel, and/or the different licorice descriptor references. In fact, licorice flavor and aftertaste evaluated after 1 min have been found for acesulfame-K when compared to a carbohydrate sweetener using a descriptive analysis procedure (Portmann & Kilcast, 1998). Furthermore, in agreement with our study, a significantly lower intensity of honey taste compared to sucrose was found in the attack period by Tan et al. (2019), whereas similar intensities were observed in the beginning of the temporal profile.

Throughout all periods examined, a bitter taste was perceived for aspartame, which is in agreement with what has been reported by other authors (Larson-Powers & Pangborn, 1978; Tan et al., 2019). However, Reyes et al. (2017) and Ott et al. (1991) did not report any bitterness for aspartame using TCATA and time–intensity, respectively. As mentioned previously, the difference found by Reyes et al. (2017) might be explained by the fact that their consumer panel had received no training, which hindered their ability to detect low levels of bitterness and to discriminate basic tastes (O'Mahony et al., 1979). Trained panel assessors, on the other hand, are screened and selected according to their basic taste discrimination and detection capabilities (ISO, 2012). Ott et al. (1991) found that the bitterness of aspartame had increased to an insignificant degree compared to sucrose throughout the evaluation period. However, if the evaluation of aspartame was performed within the same session as acesulfame-K, the strong bitterness of the latter compound may have masked any subtle bitterness of aspartame. Since the sample serving sequence is not addressed in their protocol, this remains a possibility, though it should be mentioned that the authors state that they did control for carry-over effects between samples. Furthermore, similar to the outcomes for acesulfame-K, Reyes et al. (2017) found no licorice flavor for aspartame, possibly for the same reason as stated above for acesulfame-K. However, licorice flavor and aftertaste evaluated after 1 min have been found for aspartame when compared to sucrose in a study using a descriptive analysis procedure (Portmann & Kilcast, 1996).

In the aftertaste period, erythritol was found to elicit bitterness when compared to sucrose. This finding was also observed by Tan et al. (2019), who reported a small increase in bitterness compared to sucrose in the middle of the evaluation period of temporal curve, but no difference in the overall area under the curve for bitterness.

Tian et al. (2022) evaluated the temporal profile of rebaudioside M considering sweetness and bitterness. They reported a very low bitterness intensity present only in the first 20 s of the evaluation with a peak at 10 s, whereas bitter was perceived in both the attack and aftertaste periods in this study. This discrepancy could be attributed to the use of time–intensity in the study of Tian et al. (2022). In contrast to our results, reporting a strong licorice flavor for the 100%

sucrose-replaced rebaudioside M sample, Tao and Cho (2020) did not find any differences for licorice off-flavor between 100% replaced rebaudioside M, D, and A and sucrose samples when using consumer CATA (Tao & Cho, 2020). An explanation might be that these consumers were not familiar with the licorice flavor, as they were not provided with a reference. In fact, several studies have found licorice to be a descriptor for rebaudioside A (Kim et al., 2015; Portmann & Kilcast, 1996; Reyes et al., 2017).

Confirming our results, Reyes et al. (2017) found great similarity between sucralose and sucrose temporal profiles. Tan et al. (2019) used a 0.0387% concentration, a substantial higher concentration than used here, and found a bitter taste when the temporal profile of sucralose was compared to sucrose. However, no difference in the area under the curve of bitterness was found.

Differences were seen when comparing the temporal profile of the sucrose controls from the different sweetener sessions (Figures S1–S5). An example of this is a notably higher citation of honey in the attack phase when the sucrose control in the ace-K session (Figure S1) is compared with the other sucrose controls (Figures S2–S5). This might be explained as an artifact of the dissimilarities between the individual sweeteners and sucrose. As a substantial contrast to sucrose, the sweetener ace-K, elicits notable side-tastes and off-flavors (e.g., much higher bitterness citation proportions compared with the other sweeteners). Thus, the flavors of sucrose become more pronounced when tasted in a sample set with ace-K. This is not to be confused with a carry-over effect, that we have tried to minimize with sample randomization and introduction of a 100 s break between samples. These variations in the sensory profile of a sucrose sample when tested with different sweeteners is also evident in other studies (Heikel et al., 2012).

4.5 | Implications for sucrose replacement in complex matrices

In this study, sweeteners were applied in aqueous solutions, and thus the temporal sensory profile of the samples only reflects the interaction between the sweetener and sucrose. Application of non-nutritive sweeteners in complex beverage matrices may achieve higher replacement levels compared to aqueous solutions, as constituents of the matrix can interact with the sweeteners through taste–taste (Junge et al., 2022; Keast & Breslin, 2003), taste–flavor (Calvino et al., 1990), and taste–texture (Wagoner et al., 2018) interactions potentially masking their off-flavors, off-tastes, and lingering sensations. Gotow et al. (2018) investigated the interaction between sweeteners and a coffee matrix and found a lingering sweetness from acesulfame-K and sucralose in aqueous solutions when compared to sucrose. However, when the same sweeteners were applied in a coffee matrix, the intensity of the sweetness throughout the temporal profile increased and no difference was found. This indicated that the sweetness profile of the different sweeteners was masked by the coffee matrix. Additionally, other studies investigating the temporal profile of full sucrose replacement in beverage matrices have shown successful replacement of 10% and 10.7% with sucralose in orange juice and a tamarind-based beverage, respectively, with only minor effects on the temporal sensory profile (Medeiros et al., 2022; Sousa Lima et al., 2021; Zorn et al., 2014), thus confirming the high level (%) of achievable replacement with sucralose observed in this study. However, significant changes in the temporal profile compared to the sucrose control were found when acesulfame-K (Sousa Lima et al., 2021) and rebaudioside (Sousa Lima et al., 2021; Zorn et al., 2014) were added to these beverages. This suggests that sweeteners have different levels of applicability across different beverage matrices (Hossenlopp et al., 1990; Tan et al., 2020).

5 | CONCLUSION

A range of synthetic and naturally occurring sweeteners were able to replace sucrose without altering the temporal profile. However, the achievable level of sucrose replacement was highly dependent on the sweetener applied and varied from 75% replacement as seen for aspartame, erythritol, and sucralose to 25% replacement for acesulfame-K and rebaudioside M. Replacement of 100% with aspartame, erythritol, and sucralose resulted in significant changes in the attributes bitter, cooling, and licorice, whereas bitter and licorice dominated at 50% replacement with acesulfame-K and rebaudioside M. Total replacement of sucrose in beverages while maintaining a sucrose-like temporal profile may not be a realistic goal with the sweeteners tested in this study.

AUTHOR CONTRIBUTIONS

Glenn H. Andersen: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing—original draft; writing—review & editing. **Niki Alexi**: Conceptualization; investigation; methodology; supervision; validation; writing—review & editing. **Konstantina Sfyra**: Conceptualization; investigation; methodology; supervision; validation; writing—review & editing. **Derek V. Byrne**: Conceptualization; funding acquisition; methodology; project administration; resources; supervision; validation; writing—review & editing. **Ulla Kidmose**: Conceptualization; funding acquisition; methodology; project administration; resources; supervision; validation; writing—review & editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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