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Temporal Sweetness and Side Tastes Profiles of 16 Sweeteners Using Temporal Check-all-that-Apply (TCATA)

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Abstract

An increase in consumer awareness around the negative health impacts of consuming excess added sugars has led to a rise in the replacement of sucrose in foods and beverages. This replacement is often through the use of low or no calorie sweeteners to reduce total calories while maintaining sweetness and palatability. There are a wide variety of sweeteners with diverse physical and caloric compositions which can be used at concentrations estimated to be equi-sweet to sucrose in food products. However, many of the available sweeteners are known to differ in their temporal profiles and may have other side and aftertastes alongside sweetness that need to be considered when comparing their suitability as potential sucrose substitutes. The objective of the current study was to profile and compare the temporal sweetness and qualitative differences of 15 sweeteners to sucrose across nutritive saccharide (sucrose, dextrose, fructose, allulose (D-psicose), palatinose (isomaltulose), sucrose-allulose mixture), nutritive polyol (maltitol, erythritol, mannitol, xylitol, sorbitol) and non-nutritive (acesulfame-k, aspartame, sucralose, stevia (rebaudioside-A or rebA), *luo han guo* (monk fruit extract or mogroside)) groups, at equi-sweet intensity to 10% w/v sucrose based on a previous psychophysical dose-response study . Using the Temporal Check-all-that-Apply (TCATA) method, 20 participants evaluated a set of 17 sweetener samples (including a sucrose duplicate) in triplicates across three 1-hour sessions for the occurrence of six attributes (sweetness, bitterness, metallic taste, chemical taste, honey taste and mouth-drying) over a 60 second period. Sucrose was characterised by a rapid sweetness onset (within first 10 seconds) to peak citation, and subsequent decay of sweetness with minimal side tastes noted. Acesulfame-K, stevia (rebA) and *luo han guo* had prominent and long-lasting citations of the undesirable bitter, metallic and chemical side tastes and significantly lower sweetness citations. Allulose, erythritol, sorbitol, aspartame and sucralose were perceived to have bitter, metallic and chemical side tastes, but retained a largely sweet taste profile, with longer residual sweetness for aspartame and sucralose. Nutritive sweeteners dextrose, fructose, maltitol, mannitol, sucrose-allulose mixture, palatinose and xylitol had the most similar temporal and qualitative taste profiles when compared to sucrose, in terms of their sweetness onset, peak sweetness citations, sweetness decay, and side taste profiles.

Keywords

Sweeteners, sugar, sucrose reduction, temporal profile, time-intensity, temporal check-all-that-apply

1. Introduction

The popularity of low-calorie or non-nutritive sweeteners has risen in recent years in response to consumer demand for sugar reduction or replacement across a wide range of foods and beverages (Sylvetsky & Rother, 2016). There are currently many commercially available sweeteners that are capable of matching the perceived sweetness intensity of sucrose over a range of concentrations, and with fewer calories (Antenucci & Hayes, 2015; Fujimaru, Park, & Lim, 2012; Wee, Tan, & Forde, 2018). Many of these sweeteners have advantages as sucrose substitutes such as providing bulk, having an anti-glycaemic effect, being low-cost, or supporting a clean label (Clemens et al., 2016; Lê, Robin, & Roger, 2016). Whilst maintaining equi-sweetness intensity is an important criteria for sugar reduction, it is not the only taste quality that is impacted when sweeteners are used to replace the sweetness of sucrose. Many sweeteners have other side tastes in addition to sweetness such as bitterness and metallic taste (Antenucci & Hayes, 2015; Fujimaru et al., 2012; Reyes, Castura, & Hayes, 2017), which strongly influence sweetness perception and product acceptability. Taste quality and intensity undergo temporal changes during consumption, with considerable differences in sweetener profile in terms of onset, persistence and decay over time (Ayya & Lawless, 1992; DuBois & Lee, 1983).

Temporal sensory methods offer the evaluation of many dynamic sensations detected in the mouth (Castura, Antúnez, Giménez, & Ares, 2016). This can be applicable for the continuous tracking of changes in a sweetener's taste profile during and immediately after consumption. Most studies on temporal differences in sweeteners have employed traditional time-intensity (T-I) approaches whereby panelists are required to document changes in the intensity for a specified sensory attribute over a fixed time period (Duizer, Bloom, & Findlay, 1997; Ketelsen, Keay, & Wiet, 1993; Lee III & Pangborn, 1986; Ott, Edwards, & Palmer, 1991; Swartz, 1980). A more recent technique is temporal dominance of sensation (TDS) (Pineau et al., 2009) whereby panelists select the most dominant sensation or taste at a particular time point from a limited set of attributes within a fixed evaluation time period (Pineau et al., 2009). Both T-I and sometimes TDS methods require ratings of perceived attribute intensity and have been completed with trained and consumer panels (DuBois & Lee, 1983; Duizer et al., 1997; Temple, Laing, Hutchinson, & Jinks, 2002). The temporal check-all-that-apply (TCATA) approach has recently been developed as a consumer-friendly technique that enables tracking of multiple sensory attributes over time. TCATA allows for the selection of sweetness and side tastes as they are perceived, making it an effective and unbiased technique to study the varying temporal taste profiles of different sweeteners (Castura et al., 2016; Reyes et al., 2017). A feature of TCATA approach is that it can be used with untrained consumers, and does not require participants to rate attribute intensity, but instead they are asked to select attributes they perceive at intervals to produce 'citation proportions' at different time points during and immediately after consumption (Castura et al., 2016). Citation proportions are the frequencies at which participants select an attribute at a given time point to track the peak occurrence and decay for each attribute. Though not a direct measure of perceived intensity, citation proportions are correlated to 'intensity' with higher citations often reported for more intense sensations (Castura et al., 2016; Reinbach, Giacalone, Ribeiro, Bredie, & Frøst, 2014). TCATA therefore enables relative comparison of sweeteners across a series of key temporal parameters such as peak citation, time to peak citation, total duration of individual attributes perceived and area under the curve for attributes.

The temporal sweetness and qualitative profiles have previously been characterised for several common commercially available nutritive and non-nutritive sweeteners using the TCATA approach (Reyes et al., 2017), and have demonstrated the interplay between sweetness intensity and the occurrence of side tastes (i.e. bitter, metallic, liquorice, cooling, drying) during a 60-seconds taste evaluation. To date, the temporal taste profiles for many newer sweeteners such as allulose, palatinose, sucrose-allulose mixture, *luo han guo*, and several polyols have yet to be characterised (Ayya & Lawless, 1992; Ketelsen et al., 1993; Swartz, 1980). The rare sugar allulose (d-psicose) and the isomerised sucrose palatinose (isomaltulose) have gained interest in recent years due to their natural source, sweet taste with minimal to no side tastes, lower calories and post-ingestive anti-glycaemic effects (Hayashi et al., 2010; Holub et al., 2010; Iida et al., 2008). Polyol sweeteners have also been reported to have sweetness profiles similar to that of sucrose with minimal to no side tastes (Grembecka, 2015; Wee et al., 2018), with fewer calories than sucrose and can also act as bulking agents in sucrose reduced foods, giving them an advantage over several high-potency non-nutritive sweeteners (Livesey, 2001; Zumbe, Lee, & Storey, 2001). The current study therefore sought to characterise the temporal sweetness and side-taste profiles across a wide range of sweeteners to sucrose using the TCATA approach. Sweetener profiles were compared to sucrose for (i) sweetness onset (time to peak sweetness), (ii) peak sweetness (maximum citation proportion), (iii) sweetness decay (negative slope after peak sweetness), (iv) differences in attribute citations compared to sucrose and (v) area under curve (AUC) across attributes.

2. Materials and Methods

2.1 Materials

The commercial sweeteners were chosen at concentrations that were estimated to be equi-sweet to a 10% w/v sucrose solution, which is the amount used in many commercial beverages (Ventura, Davis, & Goran, 2011), based on a previous psychophysical dose-response study (Wee et al., 2018). The sweeteners profiled are summarised in Table 1, and included sucrose (SIS, NTUC Fairprice Supermarket, Singapore), dextrose monohydrate (Suntop Enterprise, Singapore), fructose (Suntop Enterprise, Singapore), allulose (D-psicose; Matsutani Co., Japan), palatinose (isomaltulose; Beneo, France), xylitol (Roquette, France), sorbitol (Suntop Enterprise, Singapore), mannitol (Roquette, France), erythritol (iHerb, USA), acesulfame-K (Celanese, USA), sucralose (Tate & Lyle, USA), aspartame (Suntop Enterprise, Singapore), *luo han guo* extract (50.6% Mogroside V; Hunan Huacheng Biotech Inc., China) and stevia (68.0% Rebaudioside A; Suntop Enterprise, Singapore). The sucrose-allulose mixture was prepared as a 1:1 ratio of sucrose and allulose by weight. Table 1 lists the energy content of the sweeteners and the concentrations used in this study.

2.2 Participants

A taste panel (3 males and 17 females; mean age: 26 $\pm$ 5 years) with prior experience in the sensory evaluation of sweeteners were recruited from a participant database at the National University of

Singapore. Participants were pre-screened for eligibility and sensitivity to the basic tastes, and recruitment criteria included age (21-50 years), normal weight (BMI 20-25 kg/m^2), non-smoker, non-denture wearer, no self-reported sinus problems, not currently following a special diet, no specific food dislikes, allergies or intolerances, not phenylketonuric, diabetic or currently pregnant. All eligible participants then provided informed consent and were compensated for their time. This study (ref: 2017/00787) was approved by the Domain Specific Review Board of the National Healthcare Group, Singapore and complies with the Declaration of Helsinki for research involving human subjects.

2.3 Training and Test Procedure

All participants underwent training to ensure familiarity with the taste attributes and TCATA Fading method. This approach features participants selecting attribute terms that are applicable in describing the sample tested. Term selection was made transient by a process of automatic fading whereby selected terms gradually become unselected over a predefined short duration (i.e. 10 s in this study) (Ares et al., 2016; Castura et al., 2016). During pre-test training, participants were instructed on how to use the TCATA Fading method to evaluate sample attributes and given the opportunity to practice rating attributes. They were presented with a tastant series of 17 sweeteners consisting of 16 sweeteners at concentrations listed in Table 1, and a duplicate sucrose sample as an internal control and measure of rating consistency. Attributes and definitions from previous studies on similar sweeteners (Fujimaru et al., 2012; Reyes et al., 2017) were selected and pilot tested in house to determine the provisional list of attributes and definitions used in the training. Participants then received the provisional list of attributes and definitions and were asked to refine and clarify attributes where applicable, and to confirm that the attributes described the perceptual properties of the sweetener samples they tasted during a familiarisation session. The final list of attributes and definitions used in the study did not differ from the provisional list and is listed in Table 2. The temporal profiles of the two sucrose samples were compared to confirm the panel understood the method and had evaluated the samples consistently. The panel proceeded to the test session when there were no significant differences between the two sucrose samples for all attributes across all time points.

The same sweeteners (Table 1), including a duplicate sucrose control, were evaluated in triplicates over three 1-hour test sessions, with a minimum of 24 hours washout period between sessions. Sample presentation was randomised to mitigate the impact of potential response bias and carryover effects due to presentation order. All samples were presented in 10ml aliquots in three-digit coded glass vials at room temperature. Participants placed the entire sample in their mouth, swirled for 5 seconds and then swallowed the sample, based on a previously published approach (Reyes et al., 2017). After swallowing, participants selected attributes for a 60-second period using the TCATA Fading method. On selecting a perceived attribute, the attribute button shows up as yellow to indicate that it has been selected. The yellow colour of the button starts to fade as soon as it has been selected, and fades completely after 10 seconds to indicate that the attribute has been deselected. Participants were instructed to select applicable term(s) again for as long as they could be perceived. As with sample presentation, attributes were randomised across participants to mitigate presentation order effects. With the TCATA Fading approach, it is possible for participants to select terms that describe a sample at a given time point without having to unselect terms that are no longer perceived as compared to the original TCATA approach (Ares et al., 2016). Participants were instructed to cleanse their palate thoroughly with filtered water for one minute between samples. All data was collected using computerised data acquisition software (Compusense Cloud, Guelph, Ontario, Canada), in sensory booths which conform with international standards for the design of test rooms (ISO, 1988).

2.4 Data Analysis

Temporal curves were obtained using the tempR package (Castura, 2017) with the R-software version 3.4.4 (R Core Team, 2018). The tempR package follows a previously published protocol (Meyners & Castura, 2018), by calculating the average citation proportions for each attribute (y axis) over time (x axis; 60 seconds) for each sweetener. Averages were derived across all participants and replicates to produce a single temporal curve for each sweetener and its attributes. The citation proportion refers to the number of participants citing an attribute at each time-point within the 60 second sampling period for that sweetener sample, expressed as a proportion of the participants. To investigate differences in temporal and qualitative profiles for each sweetener in comparison to sucrose, the citation proportions for each attribute for all sweeteners were compared to sucrose. Significant differences between sucrose and the sweeteners at different time points were determined using randomization tests with significance level set at 5% ($p < 0.05$). A significant difference from sucrose for a particular attribute is represented as an overlaying bold line, and the citation proportion of sucrose is represented by dotted lines at the relevant time point(s) for when significant differences were observed. Significant differences in AUC values between sucrose and a sweetener for each attribute were determined using a mixed effects model as described in McMahon, Culver, Castura, and Ross (2017).

3. Results

3.1 Temporal Sweetness Profiles of Sweeteners

The temporal profiles for all sweeteners are shown in Figures 1, 2 and 3 respectively. The sweetness profile of sucrose (Figure 1a) was characterised by a rapid onset of sweetness to peak citation proportion (0.94) (Table 3), followed by sweetness decay as indicated by the decreasing sweetness citation until the end of the 60 seconds evaluation. All sweeteners reached peak sweetness citation within approximately the same time-frame (between 8 to 9 seconds) (Table 3). Dextrose (Figure 1d), fructose (Figure 1e), sucrose-allulose mixture (Figure 1b), palatinose (Figure 1f), maltitol (Figure 2b), mannitol (Figure 2c), xylitol (Figure 2e), aspartame (Figure 3b) and sucralose (Figure 3e) were not significantly different from sucrose in terms of peak sweetness citations. Allulose (Figure 1c), erythritol (Figure 2a), sorbitol (Figure 2d), acesulfame-K (Figure 3a), luo han guo (Figure 3c) and stevia (rebA) (Figure 3d) had significantly lower peak sweetness citations compared to sucrose, suggesting lower peak sweetness intensity. Sucrose recorded the highest peak sweetness citation, while acesulfame-K had the lowest peak sweetness citation (0.72) (Table 3). Acesulfame-K, allulose, dextrose, fructose, maltitol and sucrose-allulose mixture had similar sweetness decay to sucrose, whereas aspartame, erythritol, luo han guo and sucralose had somewhat broader peaks and longer residual sweetness. Sucralose and aspartame in particular, had significantly higher sweetness citations than sucrose towards the later stages of evaluation (~30-60 s), and also significantly higher area under the curves (AUCs; Table 4) when compared to sucrose. Mannitol, palatinose, sorbitol, stevia (rebA) had a faster decay in sweetness citations. Whereas allulose had significantly lower sweetness citations compared to sucrose, when blended in a 1:1 mixture with sucrose, the mixture (Figure 1b) showed a near identical sweetness profile to sucrose with no significant differences.

(Figure 1 here)

(Figure 2 here)

(Figure 3 here)

3.2 Temporal Side Taste Profiles of Each Sweetener

Sucrose (Figure 1a) had low citation proportions for bitterness, chemical and metallic taste (< 0.2 across all time points), with chemical taste citations higher than bitterness and metallic taste. The attribute 'honey taste' evolved similarly with sweetness, with citations coinciding with peak sweetness citations. Mouth-drying gradually increased towards the end of the evaluation (40-60 s). Dextrose (Figure 1d), fructose (Figure 1e), maltitol (Figure 2b), mannitol (Figure 2c), sucrose-allulose mixture (Figure 1b), palatinose (Figure 1f) and xylitol (Figure 2e) were most comparable to sucrose, having the fewest attributes that were cited significantly differently from sucrose. Acesulfame-K (Figure 3a), aspartame (Figure 3b), *luo han guo* (Figure 3c), stevia (rebA) (Figure 3d), sucralose (Figure 3e), allulose (Figure 1c) and sorbitol (Figure 2d) had significantly higher bitterness citations than sucrose. Acesulfame-K (Figure 3a and Table 4) had the highest peak bitterness citation proportion and bitterness AUC amongst all sweeteners, and was also the only sweetener to have AUC for bitterness almost similar to sweetness. For these sweeteners, a significantly higher bitterness citation proportion was also often accompanied by significantly higher citation proportions for metallic taste and chemical taste compared to sucrose. Allulose had significantly higher citation proportions for bitterness, chemical and metallic taste than sucrose, however in the sucrose-allulose mixture (Figure 1b), these side tastes were no longer detected in the temporal profiles. Stevia (rebA) and *luo han guo* showed distinct bitterness, chemical and metallic taste citations which persisted throughout the evaluation, with chemical taste being the dominant attribute once initial sweetness had dissipated. These two sweeteners also had the highest peak citation proportion and AUC for chemical taste amongst all sweeteners (Table 4). Erythritol and aspartame had higher citation proportions than sucrose for chemical taste but not metallic taste. By contrast, acesulfame-K, *luo han guo*, sorbitol, stevia (rebA) and sucralose had significantly higher citation proportions for metallic taste citation than sucrose, with stevia (rebA) and *luo han guo* again having the highest AUC amongst all sweeteners for metallic taste. The citation proportions for mouth-drying increased as the evaluation progressed for all sweeteners, and only erythritol peaked significantly higher than sucrose for this attribute.

4. Discussion

The current study characterised the temporal and qualitative similarities and differences in the taste profiles of a wide range of sweeteners to sucrose. The sweetener which exhibits similar taste profiles to sucrose would be most appropriate to substitute sucrose. In addition, from a nutritional standpoint ideally the chosen sweetener would also support energy or glycaemic reductions alongside a suitable sweetness intensity and quality.

In agreement with previous studies, many of the sweeteners profiled in the current trial had a similar sweetness onset to sucrose (Ketelsen et al., 1993; Lawless & Skinner, 1979; Ott et al., 1991; Reyes et al., 2017; Schiffman, Sattely-Miller, & Bishay, 2007; Yoshida, 1986). Some previous studies have reported a delayed onset for sweetness among non-nutritive sweeteners such as *luo han guo* (Kim, Yoo, Jung, Park, & Hong, 2015; Naim et al., 2002), or a faster onset of sweetness for acesulfame-K, compared to sucrose (Ott et al., 1991; von Rymon Lipinski, 1985). The concentrations chosen for all sweeteners were selected to be equi-sweet to a 10% w/v sucrose based psychophysical dose-response behaviours reported previously (Wee et al., 2018), yet the peak sweetness citations differed across sweeteners when compared to sucrose. This may be due to a number reasons including methodological differences during sample evaluation whereby participants rated the samples based on a sip-and-spit procedure in the dose-response study and swallowed the samples in the current study. This has previously been shown to contribute to differences in perceived sensory intensity, with stronger bitter intensity perceived when swallowing rather than spitting (Running & Hayes, 2017). Participants also rated other attributes in addition to sweetness, and this could have influenced perceived sweetness intensity (Duizer et al., 1997; Ketelsen et al., 1993) or shifted attention away from sweetness (Marks, 2003; Tunaley, Thomson, & McEwan, 1987). The TCATA approach captured differences in citation reports at individual times over a 60 second period, whereas the psychophysical approach was a single intensity rating on a general labelled magnitude scale (GLMS).

Peak sweetness citation was highest for sucrose, while the other nutritive saccharide and polyol sweeteners (dextrose, fructose, maltitol, mannitol, sucrose-allulose mixture, palatinose, and xylitol) had comparable but lower peak citations, although not statistically significant. Both aspartame and sucralose had peak sweetness citations that were significantly lower than sucrose, confirming that high potency sweeteners cannot match the peak sweetness of sucrose (Antenucci & Hayes, 2015). Non-nutritive sweeteners acesulfame-K, *luo han guo*, sorbitol, stevia (rebA) and some nutritive sweeteners (allulose and erythritol) had significantly lower peak sweetness citation proportions when compared to sucrose. These sweeteners also exhibited higher citations for antagonistic side tastes such as bitterness, metallic and/or chemical taste citations, which co-occurred temporally and may have attenuated the sweetness citations (Antenucci & Hayes, 2015; Fujimaru et al., 2012; Schiffman, Booth, Losee, Pecore, & Warwick, 1995). Aspartame and sucralose were significantly more bitter and metallic than sucrose while retaining a similar sweetness to sucrose, suggesting that side taste antagonism alone did not account for differences in sweetness perception (Green, Lim, Osterhoff, Blacher, & Nachtigal, 2010; Reyes et al., 2017).

Sweeteners also differed in their temporal changes in sweetness and sucrose is often described as having a 'clean' sweet taste, referring to its quick onset, intense and short-lasting sweetness accompanied by a rapid decay in sweet aftertaste (DuBois & Lee, 1983). A lingering or residual sweetness has previously been associated with reduced acceptance in certain foods (Naim et al., 2002; Rocha & Bolini, 2015), and has been reported to be common amongst several non-nutritive sweeteners (DuBois & Prakash, 2012). Acesulfame-K, allulose, dextrose, fructose, maltitol, sucrose-allulose mixture exhibited similar onset and decay profiles to sucrose whereas aspartame and sucralose had broader peaks and longer residual sweetness perceived as inferred from the significantly higher sweetness citation proportions throughout the evaluation. This is consistent with reports from previous findings (Di Monaco, Miele, Volpe, Picone, & Cavella, 2014; Fujimaru et al., 2012; Ketelsen et al., 1993; Kim et al., 2015; Ott et al., 1991; Reyes et al., 2017; Wiet & Beyts, 1992), and has been suggested to result from the higher affinities of the non-nutritive sweetener to taste receptor binding sites, which leads to longer residual sweetness intensity (DuBois, 2016; Froloff, Lloret, Martinez, & Faurion, 1998; Fujimaru et al., 2012; Schiffman et al., 1994). In the case of stevia (rebA), the rapid decay in sweetness after the peak coincided with a sharp rise in bitterness, which has also previously been observed by Reyes et. al. (2017). In this case, bitter taste antagonism may be the mechanism, and stevia (rebA) is unlike other non-nutritive sweeteners such as aspartame, which are characterised by a slow decay and high residual sweetness and bitterness.

The temporal taste profile for sucrose was characterised by sweetness, with minimal citations for side tastes. However, several studies have demonstrated other side tastes when sucrose is consumed, such as bitterness or metallic taste at low intensities (Gwak, Chung, Kim, & Lim, 2012; Kim et al., 2015; Portmann & Kilcast, 1998; Reyes et al., 2017). This may have been due to carryover between sweeteners (Lawless & Heymann, 2010) whereas others have reported a potential 'smearing' bias where participants may rate all attributes available in an attempt to characterise an unfamiliar side taste (Reyes et al., 2017). Nutritive sweeteners had comparable side taste profiles to sucrose which was characterised by low bitterness, chemical and metallic taste citation proportions. Allulose had significantly higher bitterness citations than sucrose. However, when blended with sucrose in a 1:1 mixture, these side tastes were no longer detected. This had been previously established that blending sweeteners had shown to have a variety of advantages, including improvements to overall sensory profiles (Schiffman et al., 2007), as well as synergism in sweetness perceived (Lawless, 1998). Erythritol had a similar sweetness profile to sucrose, but also had higher chemical taste citations that emerged when the sweetness citations declined, as was also observed by Gwak et al. (2012). All other non-nutritive sweeteners had significantly higher peak bitterness, chemical and metallic taste citations than sucrose which may be challenging when used to reduce or replace sucrose. Acesulfame-K is well-known to impart relatively strong bitterness when tasted alone (Allen, McGeary, & Hayes, 2013; Kuhn et al., 2004; Schiffman et al., 1995) and may be best suited to blending with other non-nutritive sweeteners such as aspartame (Hanger, Lotz, & Lepeniotis, 1996). Stevia (rebA) and *luo han guo* had lingering chemical, bitter and metallic side tastes that were perceived through to the end of the evaluation period as inferred from the significantly higher citation proportions. Aspartame and sucralose had similar temporal profiles to sucrose, and have previously been shown to impart similar profiles to sucrose in matrices such as coffee (Azevedo, Schmidt, & Bolini, 2015) and chocolate-flavoured milk (Palazzo &

Bolini, 2014). The current study did not account for differences in individual participants genetic variability in their sensitivity to the bitter side tastes associated with certain non-nutritive sweeteners (Allen et al., 2013). A genetic predisposition to a heightened sensitivity to the bitter taste of some sweeteners has previously been shown to significantly impact on their acceptance when used to support sugar reduction (Bobowski, Reed, & Mennella, 2016).

The honey taste attribute was included to provide an indication of a ‘natural’ sweet taste that is often absent in non-nutritive sweeteners (Gwak et al., 2012; Kim et al., 2015). In the current study honey taste was not cited widely by panellists and did not differ significantly between sucrose and the other sweeteners. Citations for honey-taste peaked and declined in tandem with sweetness, and this especially the case for nutritive sweeteners. The mouth-drying attribute was also poorly discriminated amongst sweeteners with the exception of erythritol, which peaked significantly higher in this attribute than for sucrose. Polyols and non-nutritive sweeteners have previously been reported to be more mouth-drying than sucrose including acesulfame-K (Portmann & Kilcast, 1998), xylitol and stevia (rebA) (Kim et al., 2015). However, the emergence of mouth-drying towards the end of the evaluation is likely due to the depletion of salivary proteins needed for lubrication during sample evaluation (Reyes et al., 2017) rather than a taste effect of the sweetener. Low citation frequencies and poor discrimination for these two attributes suggest that the current sweetener samples did not differ significantly in these qualities.

Findings from the current study are aligned with previously reported differences in temporal sweetness profile and side tastes. Previous reports have compared temporal profiles of sweeteners at weak and moderate concentrations, and showed that peak sweetness, sweetness decay, residual sweetness, as well as intensity of side tastes are dependent on sweetener concentration (Ketelsen et al., 1993; Ott et al., 1991; Reyes et al., 2017; Schiffman et al., 1995). Furthermore, the perceived sweetness of certain sweeteners, especially non-nutritive sweeteners, do not grow at the same rate as sucrose with concentration (Moskowitz, 1970; Wee et al., 2018) and therefore differences relative to sucrose reported here may not be applicable at lower or higher concentrations. When sweeteners are used in complex foods and beverages, there will also be additional taste-taste interactions and matrix effects that can impact sweetness perception and release, and may mask or potentiate side tastes to produce temporal and qualitative profiles not captured when sweeteners are profiled in water (Bayarri, Rivas, Izquierdo, & Costell, 2007; Ketelsen et al., 1993; King, Arents, & Duineveld, 2003; Reis et al., 2011). Food matrix and taste-taste interactions should therefore be considered when evaluating the suitability of individual sweeteners to replace or reduce sucrose.

The nutritive sweeteners dextrose, fructose, maltitol, mannitol, sucrose-allulose mixture, palatinose and xylitol were found to have the most similar taste profiles to sucrose in terms of sweetness onset, peak sweetness, sweetness decay, residual sweetness and side taste profiles. In terms of calorie-savings, dextrose and palatinose do not provide substantial reductions in calories at equi-sweet concentrations to sucrose (Wee et al., 2018), which may limit their application when reformulating to produce energy-reduced products. Allulose, erythritol, sorbitol, aspartame and sucralose had higher citations for bitter, metallic or chemical side tastes than sucrose, but retain much of the same sweet taste profile. By contrast the sucrose-allulose mixture had a sweetness profile that matched sucrose, and offers the opportunity to reduce calories (Wee et al., 2018) and support a reduction in post-prandial glucose (Hayashi et al 2010).

5. Conclusion

The current paper characterised the temporal sweetness and side taste profiles of 16 sweeteners for their sweetness onset, peak sweetness, sweetness decay, and differences in attribute citations in comparison to sucrose. Dextrose, fructose, maltitol, mannitol, palatinose, sucrose-allulose mixture and xylitol shared similar temporal and side taste profiles to sucrose. By contrast, non-nutritive sweeteners acesulfame-k, *luo han guo* and stevia had profiles that most varied from sucrose, with significantly lower sweetness citation proportions and higher side tastes citation proportions recorded. The sweeteners profiled in the current study have distinct sensory, physical, nutrient and metabolic characteristics that should be considered when selecting a sweetener to replace or reduce sucrose. Future research should consider the temporal profiles of these sweeteners in food and beverage matrices to investigate how the observed sweetener profiles change in actual foods.

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References

Allen, A. L., McGeary, J. E., & Hayes, J. E. (2013). Rebaudioside A and Rebaudioside D Bitterness do not Covary with Acesulfame-K Bitterness or Polymorphisms in TAS2R9 and TAS2R31. *Chemosensory perception, 6*(3), 109-117.

Antenucci, R. G., & Hayes, J. E. (2015). Nonnutritive sweeteners are not supernormal stimuli. *International Journal of Obesity, 39*(2), 254.

Ares, G., Castura, J. C., Antúnez, L., Vidal, L., Giménez, A., Coste, B., . . . Jaeger, S. R. (2016). Comparison of two TCATA variants for dynamic sensory characterization of food products. *Food Quality and Preference, 54*, 160-172.

Ayya, N., & Lawless, H. T. (1992). Quantitative and qualitative evaluation of high-intensity sweeteners and sweetener mixtures. *Chemical Senses, 17*(3), 245-259.

Azevedo, B. M., Schmidt, F. L., & Bolini, H. M. (2015). High‐intensity sweeteners in espresso coffee: ideal and equivalent sweetness and time‐intensity analysis. *International Journal of Food Science & Technology, 50*(6), 1374-1381.

Bayarri, S., Rivas, I., Izquierdo, L., & Costell, E. (2007). Influence of texture on the temporal perception of sweetness of gelled systems. *Food research international, 40*(7), 900-908.

Castura, J. C., Antúnez, L., Giménez, A., & Ares, G. (2016). Temporal Check-All-That-Apply (TCATA): A novel dynamic method for characterizing products. *Food Quality and Preference, 47*, 79-90. doi:https://doi.org/10.1016/j.foodqual.2015.06.017

Clemens, R. A., Jones, J. M., Kern, M., Lee, S. Y., Mayhew, E. J., Slavin, J. L., & Zivanovic, S. (2016). Functionality of sugars in foods and health. *Comprehensive Reviews in Food Science and Food Safety, 15*(3), 433-470.

Di Monaco, R., Miele, N., Volpe, S., Picone, D., & Cavella, S. (2014). Temporal sweetness profile of MNEI and comparison with commercial sweeteners. *Journal of sensory studies, 29*(6), 385-394.

DuBois, G. E. (2016). Molecular mechanism of sweetness sensation. *Physiology & behavior, 164*, 453-463.

DuBois, G. E., & Lee, J. F. (1983). A simple technique for the evaluation of temporal taste properties. *Chemical Senses, 7*(3-4), 237-247.

DuBois, G. E., & Prakash, I. (2012). Non-caloric sweeteners, sweetness modulators, and sweetener enhancers. *Annual review of food science and technology, 3*, 353-380.

Duizer, L., Bloom, K., & Findlay, C. (1997). Dual-attribute time-intensity sensory evaluation: A new method for temporal measurement of sensory perceptions. *Food Quality and Preference, 8*(4), 261-269.

Froloff, N., Lloret, E., Martinez, J.-M., & Faurion, A. (1998). Cross-adaptation and molecular modeling study of receptor mechanisms common to four taste stimuli in humans. *Chemical Senses, 23*(2), 197-206.

Fujimaru, T., Park, J. H., & Lim, J. (2012). Sensory characteristics and relative sweetness of tagatose and other sweeteners. *Journal of food science, 77*(9), S323-S328.

Green, B. G., Lim, J., Osterhoff, F., Blacher, K., & Nachtigal, D. (2010). Taste mixture interactions: suppression, additivity, and the predominance of sweetness. *Physiology & behavior, 101*(5), 731-737.

Grembecka, M. (2015). Sugar alcohols—their role in the modern world of sweeteners: a review. *European Food Research and Technology, 241*(1), 1-14.

Gwak, M.-J., Chung, S.-J., Kim, Y. J., & Lim, C. S. (2012). Relative sweetness and sensory characteristics of bulk and intense sweeteners. *Food Science and Biotechnology, 21*(3), 889-894.

Hanger, L., Lotz, A., & Lepeniotis, S. (1996). Descriptive profiles of selected high intensity sweeteners (HIS), HIS blends, and sucrose. *Journal of food science, 61*(2), 456-459.

Hayashi, N., Iida, T., Yamada, T., Okuma, K., Takehara, I., Yamamoto, T., . . . Tokuda, M. (2010). Study on the postprandial blood glucose suppression effect of D-psicose in borderline diabetes and the safety of long-term ingestion by normal human subjects. *Bioscience, biotechnology, and biochemistry, 74*(3), 510-519.

Holub, I., Gostner, A., Theis, S., Nosek, L., Kudlich, T., Melcher, R., & Scheppach, W. (2010). Novel findings on the metabolic effects of the low glycaemic carbohydrate isomaltulose (Palatinose™). *British journal of nutrition, 103*(12), 1730-1737.

Iida, T., Kishimoto, Y., Yoshikawa, Y., Hayashi, N., Okuma, K., Tohi, M., . . . Izumori, K. (2008). Acute D-psicose administration decreases the glycemic responses to an oral maltodextrin tolerance test in normal adults. *Journal of nutritional science and vitaminology, 54*(6), 511-514.

ISO. (1988). Sensory analysis: General guidance for the design of test rooms. Geneva, Switzerland: International Organization for Standardization.

Ketelsen, S., Keay, C., & Wiet, S. (1993). Time‐Intensity Parameters of Selected Carbohydrate and High Potency Sweeteners. *Journal of food science, 58*(6), 1418-1421.

Kim, M.-J., Yoo, S.-H., Jung, S., Park, M.-K., & Hong, J.-H. (2015). Relative sweetness, sweetness quality, and temporal profile of xylooligosaccharides and luo han guo (Siraitia grosvenorii) extract. *Food Science and Biotechnology, 24*(3), 965-973.

King, B. M., Arents, P., & Duineveld, C. (2003). A comparison of aspartame and sucrose with respect to carryover effects in yogurt. *Food Quality and Preference, 14*(1), 75-81.

Kuhn, C., Bufe, B., Winnig, M., Hofmann, T., Frank, O., Behrens, M., . . . Meyerhof, W. (2004). Bitter taste receptors for saccharin and acesulfame K. *Journal of Neuroscience, 24*(45), 10260-10265.

Lawless, H. T. (1998). Theoretical note: tests of synergy in sweetener mixtures. *Chemical Senses, 23*(4), 447-451.

Lawless, H. T., & Skinner, E. Z. (1979). The duration and perceived intensity of sucrose taste. *Perception & psychophysics, 25*(3), 180-184.

Lê, K.-A., Robin, F., & Roger, O. (2016). Sugar replacers: from technological challenges to consequences on health. *Current opinion in clinical nutrition and metabolic care, 19*(4), 310-315.

Lee III, W., & Pangborn, M. (1986). Time-intensity: the temporal aspects of sensory perception. *Food technology (USA)*.

Livesey, G. (2001). Tolerance of low-digestible carbohydrates: a general view. *British journal of nutrition, 85*(S1), S7-S16.

Marks, L. E. (2003). The role of attention in chemosensation. *Food Quality and Preference, 14*(2), 147-155.

McMahon, K. M., Culver, C., Castura, J. C., & Ross, C. F. (2017). Perception of carbonation in sparkling wines using descriptive analysis (DA) and temporal check-all-that-apply (TCATA). *Food Quality and Preference, 59*, 14-26.

Meyners, M., & Castura, J. C. (2018). The analysis of temporal check-all-that-apply (TCATA) data. *Food Quality and Preference, 67*, 67-76. doi:https://doi.org/10.1016/j.foodqual.2017.02.003

Moskowitz, H. R. (1970). Ratio scales of sugar sweetness. *Perception & psychophysics, 7*(5), 315-320. doi:10.3758/bf03210175

Naim, M., Nir, S., Spielman, A., Noble, A., Peri, I., Rodin, S., & Samuelov-Zubare, M. (2002). *Hypothesis of receptor-dependent and receptor-independent mechanisms for bitter and sweet taste transduction: implications for slow taste onset and lingering aftertaste.* Paper presented at the ACS Symposium Series.

Ott, D., Edwards, C., & Palmer, S. (1991). Perceived Taste Intensity and Duration of Nutritive and Non‐nutritive Sweeteners in Water using Time‐intensity (T‐I) Evaluations. *Journal of food science, 56*(2), 535-542.

Palazzo, A., & Bolini, H. M. A. (2014). Multiple time‐intensity analysis: sweetness, bitterness, chocolate flavor and melting rate of chocolate with sucralose, rebaudioside and neotame. *Journal of sensory studies, 29*(1), 21-32.

Pineau, N., Schlich, P., Cordelle, S., Mathonnière, C., Issanchou, S., Imbert, A., . . . Köster, E. (2009). Temporal dominance of sensations: Construction of the TDS curves and comparison with time–intensity. *Food Quality and Preference, 20*(6), 450-455.

Portmann, M.-O., & Kilcast, D. (1998). Descriptive profiles of synergistic mixtures of bulk and intense sweeteners. *Food Quality and Preference, 9*(4), 221-229.

Reinbach, H. C., Giacalone, D., Ribeiro, L. M., Bredie, W. L., & Frøst, M. B. (2014). Comparison of three sensory profiling methods based on consumer perception: CATA, CATA with intensity and Napping®. *Food Quality and Preference, 32*, 160-166.

Reis, R. C., Minim, V. P., Bolini, H. M., Dias, B. R., Minim, L. A., & Ceresino, E. B. (2011). Sweetness equivalence of different sweeteners in strawberry‐flavored yogurt. *Journal of Food Quality, 34*(3), 163-170.

Reyes, M., Castura, J., & Hayes, J. (2017). Characterizing dynamic sensory properties of nutritive and nonnutritive sweeteners with temporal check‐all‐that‐apply. *Journal of sensory studies, 32*(3).

Rocha, I. F. d. O., & Bolini, H. M. A. (2015). Passion fruit juice with different sweeteners: sensory profile by descriptive analysis and acceptance. *Food science & nutrition, 3*(2), 129-139.

Running, C. A., & Hayes, J. E. (2017). Sip and spit or sip and swallow: Choice of method differentially alters taste intensity estimates across stimuli. *Physiology & behavior, 181*, 95-99.

Schiffman, S. S., Booth, B. J., Losee, M. L., Pecore, S. D., & Warwick, Z. S. (1995). Bitterness of sweeteners as a function of concentration. *Brain research bulletin, 36*(5), 505-513.

Schiffman, S. S., Pecore, S. D., Booth, B. J., Losee, M. L., Carr, B. T., Sattely-Miller, E., . . . Warwick, Z. S. (1994). Adaptation of sweeteners in water and in tannic acid solutions. *Physiology & behavior, 55*(3), 547-559.

Schiffman, S. S., Sattely-Miller, E. A., & Bishay, I. E. (2007). Time to maximum sweetness intensity of binary and ternary blends of sweeteners. *Food Quality and Preference, 18*(2), 405-415.

Swartz, M. (1980). Sensory screening of synthetic sweeteners using time‐intensity evaluations. *Journal of food science, 45*(3), 577-581.

Sylvetsky, A. C., & Rother, K. I. (2016). Trends in the consumption of low-calorie sweeteners. *Physiology & behavior, 164*, 446-450.

Temple, E. C., Laing, D. G., Hutchinson, I., & Jinks, A. L. (2002). Temporal Perception of Sweetness by Adults and Children Using Computerized Time—Intensity Measures. *Chemical Senses, 27*(8), 729-737.

Tunaley, A., Thomson, D., & McEwan, J. (1987). Determination of equi‐sweet concentrations of nine sweeteners using a relative rating technique. *International Journal of Food Science & Technology, 22*(6), 627-635.

Ventura, E. E., Davis, J. N., & Goran, M. I. (2011). Sugar content of popular sweetened beverages based on objective laboratory analysis: focus on fructose content. *Obesity, 19*(4), 868-874.

von Rymon Lipinski, G.-W. (1985). The new intense sweetener acesulfame K. *Food chemistry, 16*(3-4), 259-269.

Wee, M., Tan, V., & Forde, C. (2018). A Comparison of Psychophysical Dose-Response Behaviour across 16 Sweeteners. *Nutrients, 10*(11), 1632.

Wiet, S. G., & Beyts, P. K. (1992). Sensory characteristics of sucralose and other high intensity sweeteners. *Journal of food science, 57*(4), 1014-1019.

Yoshida, M.-a. (1986). A microcomputer (PC 9801/MS mouse) system to record and analyze time-intensity curves of sweetness. *Chemical Senses, 11*(1), 105-118.

Zumbe, A., Lee, A., & Storey, D. (2001). Polyols in confectionery: the route to sugar-free, reduced sugar and reduced calorie confectionery. *British journal of nutrition, 85*(S1), S31-S45.

Table 1: Concentrations and caloric content of the 16 sweeteners used.

Sweetener	Abbreviation	Kcal (kcal/g)	Concentration (% w/v)*
Acesulfame-K	ACE	0.0	0.0832
Allulose	ALL	0.2	13.31
Aspartame	ASP	4.0	0.0827
Dextrose	DEX	3.4	15.54
Erythritol	ERY	0.2	13.33
Fructose	FRU	3.7	7.37
Luo Han Guo	LHG	0.0	0.0694
Maltitol	MAL	2.7	11.22
Mannitol	MAN	1.5	14.63
Mixture	MIX	2.1	10.72
Palatinose	PAL	4.0	26.45
Sorbitol	SOR	2.5	13.74
Stevia	STE	0.0	0.0395
Sucralose	SCL	0.0	0.0387
Sucrose	SUC	4.0	10.00
Xylitol	XYL	2.5	9.85

**Concentrations are based on equi-sweet intensities to 10% w/v sucrose from previous psychophysical dose-response study (Wee et al., 2018)*

ǂ1:1 Sucrose-allulose mixture (weight basis)

Table 2: Attributes and definitions used to describe the qualitative profile of sweeteners.

Attribute	Definition
Sweetness	The sweet taste associated with table sugar in water
Bitterness	The bitter taste associated with bitter substances like caffeine
Metallic Taste	The metallic taste associated with flavour of coins and metal spoons
Chemical Taste	Chemical taste that resembles artificial flavours, medicinal or chemical substances
Honey Taste	The taste associated with honey
Mouth-drying	Sensation of the lack of lubrication or moistness, resulting in friction in mouth

Table 3: Temporal sweetness characteristics of 16 sweeteners comparing time to peak sweetness, peak sweetness citations, and sweetness AUC; *indicates significant differences between sweetener and that of the sucrose ($p \leq 0.05$)

Sweetener	Time to Peak Sweetness (s)	Peak Sweetness Citations	Sweetness AUC
Acesulfame-K	8	0.72*	20.4*
Allulose	9	0.76*	20.3*
Aspartame	8	0.88	33.8*

Dextrose	8	0.91	23.8*
Erythritol	9	0.78*	21.1*
Fructose	8	0.92	23.3*
Luo Han Guo	8	0.79*	22.9
Maltitol	8	0.87	24.1
Mannitol	8	0.87	22.0*
Mixture[ǂ]	8	0.88	25.1
Palatinose	8	0.91	25.4
Sorbitol	8	0.80*	19.2*
Stevia (rebA)	8	0.79*	21.6*
Sucralose	8	0.93	37.7*
Sucrose	8	0.94	28.2
Xylitol	8	0.85	25.4

ǂ1:1 Sucrose-allulose mixture (weight basis)

Table 4 Area under the curve (AUC) of sweeteners for all attributes; *indicates significant differences between sweetener and that of the sucrose (p≤0.05)

Sweetener	Sweetness	Bitterness	Metallic Taste	Chemical Taste	Honey Taste	Mouth-drying
Acesulfame-K	20.4*	20.3*	5.3*	11.4*	5.0	7.5
Allulose	20.3*	10.9*	3.3*	10.5	5.9	8.6
Aspartame	33.8*	5.9	3.4	14.4*	8.3	5.1
Dextrose	23.8*	2.4	3.5*	6.5	8.7	8.6
Erythritol	21.1*	1.3	2.1	11.1	6.8	12.1*
Fructose	23.3*	2.0	3.0	7.5	8.7	7.1
Luo Han Guo	22.9	12.6*	10.8*	20.7*	4.4	6.9
Maltitol	24.1	0.3	2.2	6.4	6.8	7.1
Mannitol	22.0*	1.0	3.4	9.7	7.4	7.4
Mixture[ǂ]	25.1	0.7	1.9	5.5	7.5	7.6
Palatinose	25.4	0.9	2.3	6.4	8.5	6.9
Sorbitol	19.2*	4.3	5.8*	12.8*	5.5	8.9
Stevia (RebA)	21.6*	12.4*	9.5*	22.7*	5.0	7.0
Sucralose	37.7*	3.8	5.1	12.1*	8.8	6.4
Sucrose	28.2	0.2	1.3	4.3	8.6	7.2
Xylitol	25.4	0.7	1.3	6.1	9.8	8.7

ǂ1:1 Sucrose-allulose mixture (weight basis)

Figure 1: Temporal profiles of nutritive saccharide sweeteners: (a) sucrose, (b) sucrose-allulose mixture, (c) allulose, (d) dextrose, (e) fructose and (f) palatinose. The solid lines represent the temporal profile of each attribute, and overlaying bold lines indicate significant differences in the citation proportion for an attribute when compared to sucrose at that time point. Dotted lines represents citation proportion for the attribute of sucrose where above or below a bold line represent significantly higher or lower citation proportions compared to the sweetener respectively.

Figure 2: Temporal profiles of nutritive polyol sweeteners: (a) erythritol, (b) maltitol, (c) mannitol, (d) sorbitol, and (e) xylitol. The solid lines represent the temporal profile of each attribute, and overlaying bold lines indicate significant differences in the citation proportion for an attribute when compared to sucrose at that time-point. Dotted lines represents citation proportion for the attribute of sucrose where above or below a bold line represent significantly higher or lower citation proportions compared to the sweetener respectively.

Figure 3: Temporal profiles of non-nutritive sweeteners: (a) acesulfame-K, (b) aspartame, (c) luo han guo, (d) stevia (rebA), and (e) sucralose. The solid lines represent the temporal profile of each attribute, and overlaying bold lines indicate significant differences in the citation proportion for an attribute when compared to sucrose at that time-point. Dotted lines represents citation proportion for the attribute of sucrose where above or below a bold line represent significantly higher or lower citation proportions compared to the sweetener respectively.

Highlights

- TCATA was used to compare temporal profiles of sweeteners
- Nutritive sweeteners had similar sweetness and side-taste profiles to sucrose
- Non-nutritive sweeteners had temporal profiles that varied most from sucrose
- Sucrose-allulose mixture (1:1) had similar temporal profile to sucrose
- TCATA provides dynamic sensory information useful in substituting sucrose

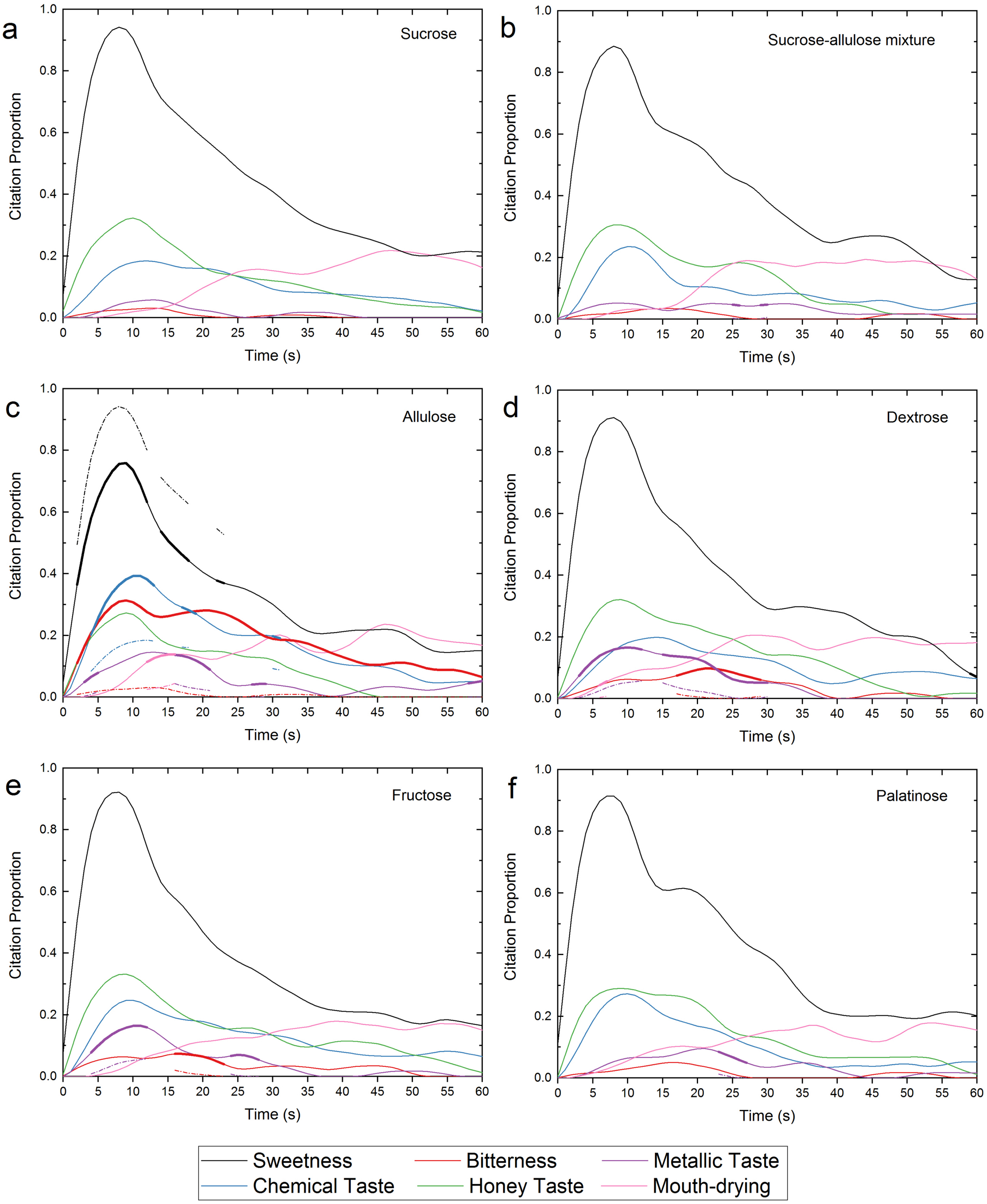
a
Sucrose
b
Sucrose-allulose mixture
c
Allulose
d
Dextrose
e
Fructose
f
Palatinose
Citation Proportion
Time (s)
Sweetness
Bitterness
Metallic Taste
Chemical Taste
Honey Taste
Mouth-drying

Figure 1

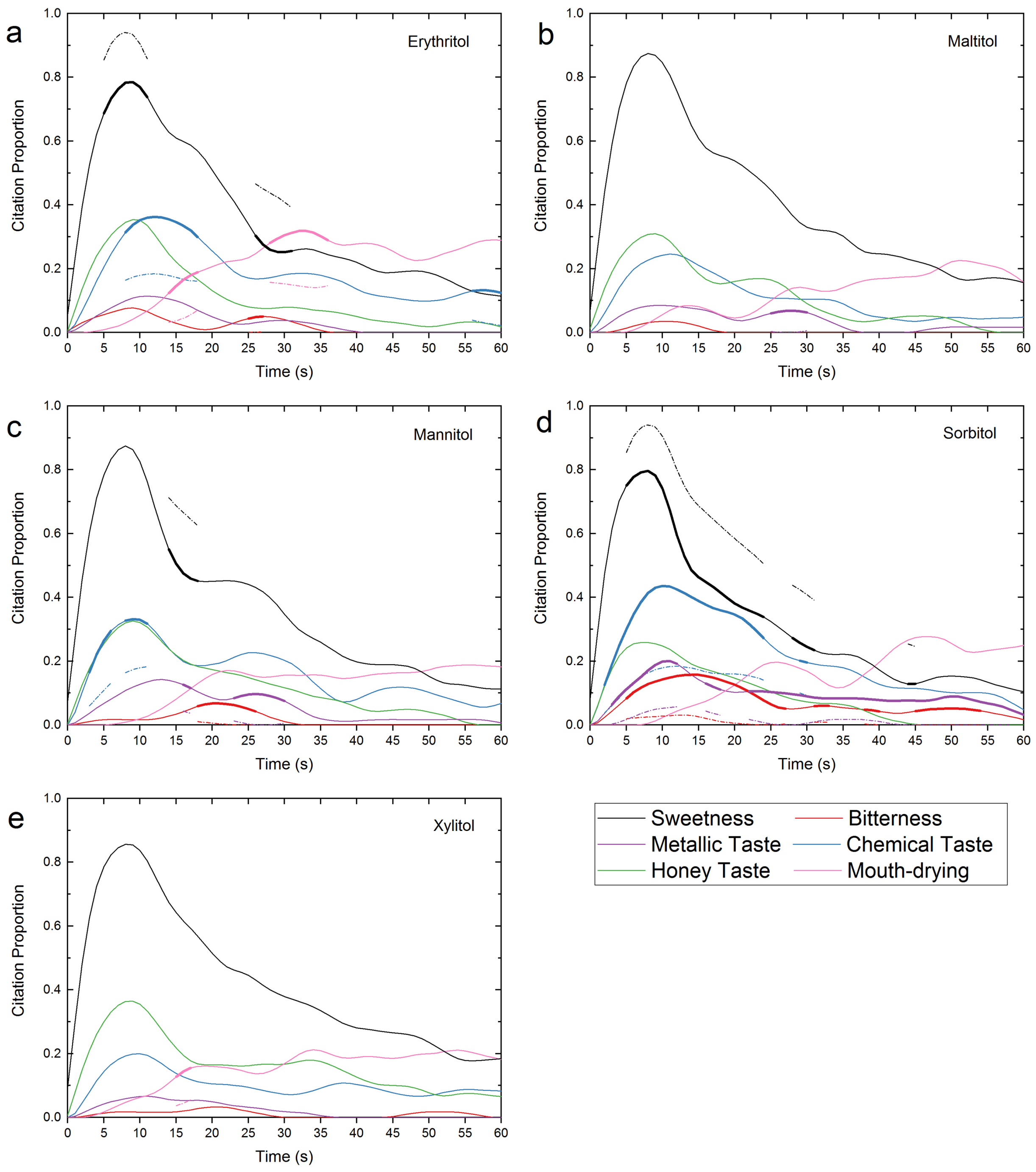
a
Erythritol
b
Maltitol
c
Mannitol
d
Sorbitol
e
Xylitol
Citation Proportion
Time (s)
Sweetness
Bitterness
Metallic Taste
Chemical Taste
Honey Taste
Mouth-drying

Figure 2

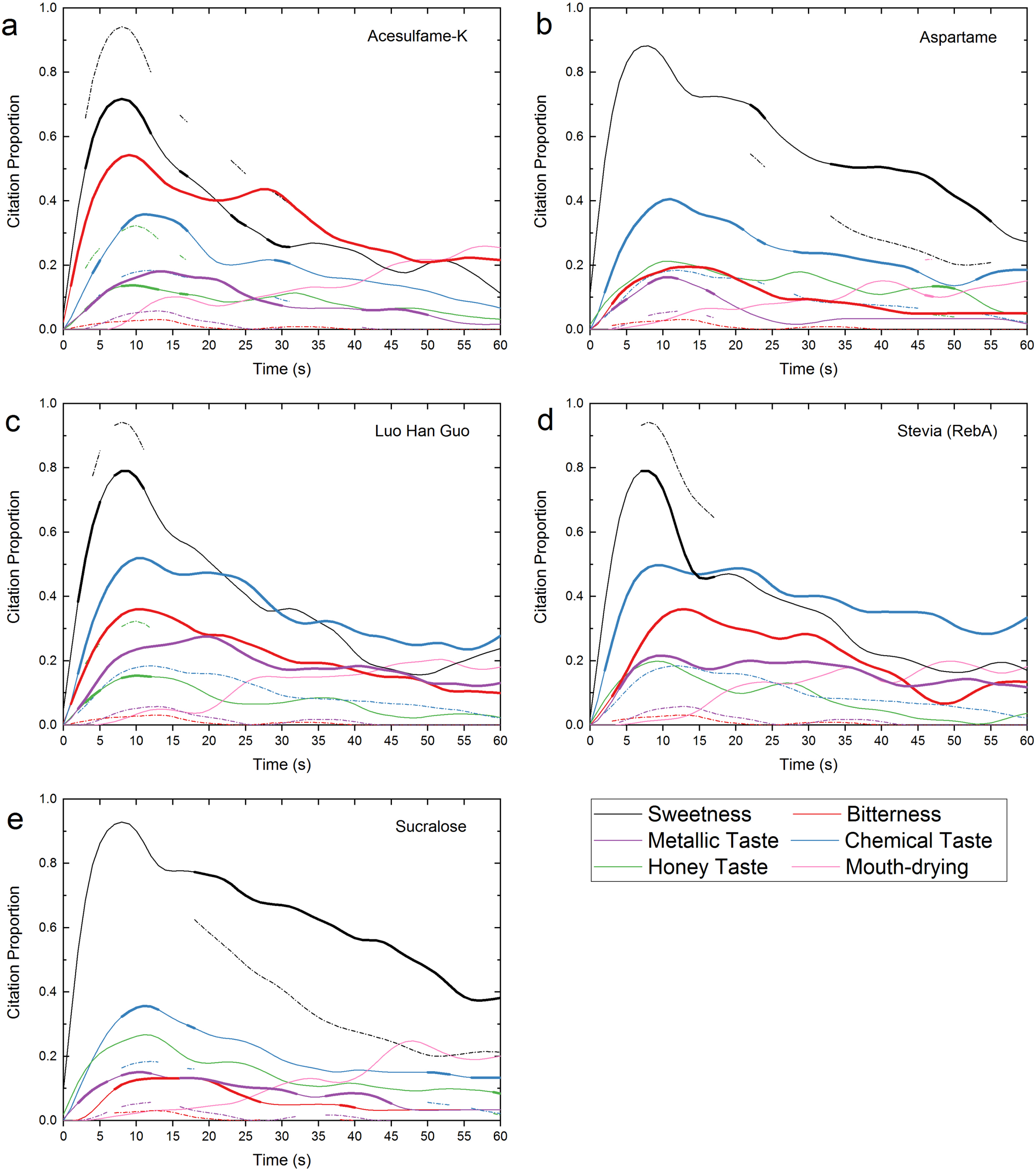
a
Acesulfame-K
b
Aspartame
c
Luo Han Guo
d
Stevia (RebA)
e
Sucralose
Citation Proportion
Time (s)
Sweetness
Bitterness
Metallic Taste
Chemical Taste
Honey Taste
Mouth-drying

Figure 3