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Cross-modal interactions as a strategy for sugar reduction in products targeted at children: Case study with vanilla milk desserts

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Abstract

The high availability of products with high sugar content, particularly among those targeted as children, has been identified as one of the factors that contribute to the childhood obesity epidemic. For this reason, product reformulation has been recommended as one of the strategies that can be implemented to achieve short-term reductions in children's sugar intake. In this context, the objective of this study was to evaluate the feasibility of using cross-modal (taste-odor-texture) interactions as a strategy for reducing the sugar content of products targeted at children, using milk desserts as case study. A series of 5 vanilla milk desserts were formulated: a control sample with 12% added sugar and 4 sugar-reduced samples (7% added sugar) prepared following a 2x2 experimental design by varying vanilla (0.4% and 0.6% w/w) and starch (4.3% and 4.7% w/w) concentrations. A total of 112 children (8 to 12 years old) tasted the desserts and performed a dynamic sensory characterization task using either temporal check-all-that-apply or temporal dominance of sensations. In addition, they assessed the overall liking of all samples. Results showed that sugar-reduced samples did not significantly differ from the control sample in terms of their average overall liking scores. However, individual differences in children's hedonic reaction were found; three clusters of children with distinctive liking patterns were identified. The increase in vanilla and starch concentration led to an increase in overall liking for over 80% of the children. Sensory dynamic profiles revealed significant but subtle differences among samples. Results from the present work suggest that cross-modal interactions could contribute to minimizing the sensory changes caused by sugar reduction, which could enable to achieve larger reductions if implemented in the context of gradual sugar reduction programs.

Keywords: *sensory characterization; TDS; TCATA; temporal methods; product development*

1. Introduction

Childhood overweight and obesity are one of the most serious health problems of the 21st century (World Health Organization (WHO), 2017). High sugar intake has been identified as one of the main dietary determinants of childhood overweight and obesity, being also a risk factor for several non-communicable diseases (Ambrosini, Johns, Northstone, Emmett, & Jebb, 2016). This has motivated the World Health Organization to recommend the implementation of public policies to reduce sugar (WHO, 2017).

Children are growing in an obesogenic environment that promotes the consumption of high energy-dense and poor-nutrient food (WHO, 2016). Products marketed at children have been reported to have excessive sugar content (Kavey, 2010; Lavriša & Pravst, 2019). Recently, Elliott & Scime (2019) evaluated the nutritional profile of food products targeted at children in the Canadian market. They found that nearly 60% of them had a poor nutritional quality, with generally a high content of sugar. Repeated exposure to these products can lead to an increased preference for sugar during childhood, which can also impact food preferences later in life (Haller, Rummel, Henneberg, Pollmer, & Köster, 1999; Nicklaus, Boggio, Chabanet, & Issanchou, 2004; Nicklaus & Remy, 2013). For this reason, product reformulation towards lower sugar content is one of the most cost-effective strategies that can be implemented to rapidly reduce sugar intake (MacGregor & Hashem, 2014).

However, reducing the sugar content of products targeted at children can be challenging due to the multiple functional properties of sugar (Goldfein & Slavin, 2015) and the importance of pleasure in children's food choices (Marty, Nicklaus, Miguet, Chambaron, & Monnery-Patris, 2018; Nguyen, Girgis, & Robinson, 2015). Therefore, in order to be effective, reformulation efforts should avoid abrupt changes in consumers' perception (Civille & Oftedal, 2012).

The use of non-nutritive sweeteners (NNS) has been the most common strategy to reduce the sugar content of food (Hutchings, Low, & Keast, 2018). However, NNS can provide undesirable sensory characteristics (DuBois & Prakash, 2012; Zorn, Alcaire, Vidal, Giménez, & Ares, 2014) and their consumption has been linked to negative health-related outcomes (Brown, de Banate, & Rother, 2010; Karalexi, Mitrogiorgou, Georgantzi, Papaevangelou, & Fessatou, 2018; Pepino, 2015; Swithers, Martin, & Davidson, 2010). Another strategy that can be used for minimizing the effects of sugar reduction in the sensory characteristics of products is the use of cross-modal interactions.

Flavor perception is the result of the integration of olfactory and gustatory inputs (Thomas-Danguin, Sinding, Tournier, & Saint-Eve, 2016). However, it is recognized that smell has a major role in the perception of flavor (Spence, 2015) and that certain aromas can modulate taste intensity (Burseg, Camacho, Knoop, & Bult, 2010; Labbe, Damevin, Vaccher, Morgenegg, & Martin, 2006). It has been documented that the addition of congruent aromas such as vanilla, caramel or fruity notes, increase sweetness perception in model solutions (Boakes & Hemberger, 2012; Schifferstein & Verlegh, 1996; R. J. Stevenson, 1999; C. Tournier et al., 2009).

Smell and flavor may be influenced by other sensory inputs such as texture, sound and color (Thomas-Danguin et al., 2016). Texture-taste interactions have demonstrated to affect the flavor perception of food (González-Tomás, Bayarri, Taylor, & Costell, 2007). It is known that many thickening agents induce a reduction in sweetness perception (Poinot et al., 2013; Ruth, Witte, & Uriarte, 2004). However, it is also accepted that the magnitude of this effect is highly dependent of the type of agent (Poinot et al., 2013). For example, starch has been shown to have a lower impact on the sweetness perception compared to carboxymethyl cellulose (CMC) and guar gum (Vaisey, Brunon, & Cooper, 1969) and has been reported to increase the sweetness perception of sucrose water solutions (Kanemaru, Harada, Kasahara, 2002).

Cross-modal interactions can be explained by multiple physicochemical and cognitive mechanisms. Taste compounds influence the concentration of volatiles in the headspace and the presence of structuring agents may hinder or facilitate their release

(Poinot et al., 2013). In addition, molecular interactions between compounds and matrix structure changes could affect their diffusion during oral processing (Thomas-Danguin et al., 2016;Tournier, Sulmont-Rossé, & Guichard, 2007). For instance, Van Ruth, De Witte & Uriarte (2004) showed that different types and concentrations of texturing agent modified the sweetness perception and the flavor release in milk desserts.

Cross-modal interactions may also be explained through experience (Spence, 2015). Stevenson, Prescott, & Boakes (1995) showed the role of associative learning in the formation of odor-taste qualities by pairing unfamiliar odors with sucrose or citric acid solutions. They demonstrated that those aromas were perceived sweeter or sourer in posterior sniffing tests. Prior co-exposure of particular aromas, tastes and textures encodes specific associations in the memory which can be evoked in later encounters with the individual qualities (Prescott, 2015). For example, Saint-Eve, Paçi Kora, & Martin (2004) found that the addition of coconut and butter aromas to low-fat yogurts has a major impact on the thickness perception compared to those considered smoother but containing green apple and almond aromas.

Recently, Alcaire, Antúnez, Vidal, Giménez, & Ares (2017) reported the use of cross-modal interactions to enhance the sweetness perception in sugar reduced milk desserts. The increase of vanilla aroma and starch concentration was able to minimize the sensory changes in sugar reduced samples among adults. Despite the potential of cross-modal interactions in the context of sugar reduction, limited studies have been published. In particular, to the authors' knowledge no studies have been reported assessing the impact of cross-modal interactions with children. The effectiveness of this strategy could diverge from the results reported for adults due to the distinctive traits governing children's sensory perception and because of the shorter prior co-exposure in children as compared to adults. For instance, differences in aroma and taste sensitivity between children and adults may impact their ability to identify changes in the sensory characteristics of sugar reduced foods (Popper & Kroll, 2011). Moreover, taking into consideration that differences in sweetness perception and preference between children and adults have been documented (Mennella et al., 2014), the topic is worth of investigation.

In this context, the objective of this study was to evaluate the feasibility of applying cross-modal interactions (taste-odor-texture) for sugar reduction in products targeted at children. Milk desserts were considered as case study given that they are an important source of added sugar in children´s diets (Bailey, Fulgoni, Cowan, & Gaine, 2018) and that they are frequently marketed as healthful alternatives for snack and dessert.

The effect of sugar reduction and cross-modal interactions on both hedonic response and sensory perception of children was studied. Current sensory methods to analyze cross-modals interactions include both static and dynamic methods (Poinot et al., 2013). The last ones have drawn attention since they consider how perception evolves during food consumption (Cadena, Vidal, Ares, & Varela, 2014) which could better capture the complexity of food perception and its relationship to consumer liking. Temporal Dominance of Sensations (TDS) is one of the most popular methods for dynamic sensory characterization, and consists in presenting a list of attributes to the assessors and ask them which one is perceived as dominant over consumption (Pineau et al., 2009). Another dynamic method that has gained popularity is Temporal Check-All-That-Apply (TCATA). TCATA was introduced by Castura, Antúnez, Giménez, and Ares (2016) as an extension of Check-All-That-Apply questions. In this method a list of attributes is presented to the assessors and they are asked to select all the terms they consider applicable to describe the sample at each moment of product evaluation and uncheck them when they are no longer applicable. To the best of the author's knowledge, none of these methods has been used with children before. As there were no available evidence of the superiority of one method or the other for the current application, both TCATA and TDS were used for dynamic sensory characterization of the samples.

2. Materials and Methods

2.1. Samples

A control sample was formulated with an added sugar concentration similar to the most popular milk desserts targeted at children in the Uruguayan market (12% w/w). Then, a series of sugar-reduced samples were developed with an added sugar concentration of 7% w/w, which corresponds to a reduction of 41.6% of added sugar or 30% of total sugar (added sugar + lactose in milk). This added sugar concentration was selected based on the Uruguayan front-of-package regulation to avoid the inclusion of a warning label for "excess of sugar" (Ministerio de Salud, 2018).

A 2x2 experimental design considering vanilla and starch concentration was used to obtain different sugar-reduced samples and assess cross-modal (taste-odor-texture) interactions. Starch concentration was increased from 4.3% w/w to 4.7% w/w to evaluate the impact of increasing firmness on children's sensory and hedonic perception. Concentrations were selected based on preliminary studies.

The effect of increasing vanilla concentration was also assessed to evaluate the influence of flavor on children's' sweetness and hedonic perception of the desserts. Two approaches were tested in preliminary studies: increasing the concentration of vanilla from 0.4% w/w to 0.6% w/w by adding an extra amount (0.20% w/w) of the same vanilla flavoring (Vanilla A -Aryes, Brazil-) and adding the same amount (0.2% w/w) of a different vanilla flavoring (Vanilla B -PLUS 3, Brun & Cía., Uruguay-). The volatile composition of the vanilla flavorings is shown in Supplementary Material 1. Paired comparisons with a panel of 11 assessors were used to evaluate the effect of increase of Vanilla A and addition of Vanilla B on the sweetness of the desserts. Evaluations were performed in duplicate. Results showed that increasing the concentration of Vanilla A did not lead to a significant increase in sweetness perception ($p=0.584$), whereas the addition of vanilla B increased sweetness intensity ($p<0.05$). Based on these results, it was decided to select the addition of Vanilla B as the high level of Vanilla (Table 1).

The sugar, starch and vanilla concentrations of the samples included in the research are shown in Table 1. All samples were prepared using a base formulation containing whole milk (3.2% fat and 4.7% carbohydrates) (Ta-Ta SA, Uruguay), 0.1% w/w polyphosphate, 0.02% w/w carrageenan (Ticaloid® 710H Stabilizer - Texture Innovation Center, TIC GUMS, Philadelphia). Samples were prepared using a Thermomix (Vorwerk Mexico S. de R.L. de C.V., Mexico D.F., Mexico). Powdered ingredients were mixed with the whole milk and heated at 90°C under constant stirring for 5 min. After the heating process, the vanilla was added to the mixture and stirred for 1 min. Desserts were placed in glass jars and stored for 24h at refrigeration temperature prior to the evaluation.

Please insert Table 1 around here

2.2. Participants

A total of 112 children (8–12 years old, 54% girls) were recruited from two elementary schools in Montevideo (Uruguay). One of the parents signed informed consent forms to allow their children to participate in the study, whereas children provided written assent to participate. Children were explained that their participation was voluntary and that they could withdraw at any time. Ethical approval was obtained from the Ethics Committee of the School of Chemistry of Universidad de la República.

2.3. Experimental procedure

The study took place in a separate quiet room in each elementary school between 10 am and 12:30 pm. Groups of 5-7 children performed the study at a time with the assistance of 3 researchers. The whole study lasted between 15 and 20 min per child.

The study was conducted on Ipads (Apple, California, USA) using Compusense Cloud (Compusense Inc, Guelph, Canada) and it was presented to children as a "secret mission" to fulfill. The secret mission framework was intended to gamify the task, and make it more enticing to children. The instructions were given by a cartoon character (a detective monkey).

The study consisted of two tasks: a familiarization step and a sample testing, involving dynamic sensory characterization and hedonic evaluation of the samples. Children were divided into two groups, each of which used a different method for evaluating the temporal sensory characteristics of the desserts: TCATA (n=53) or TDS (n=59). Chi-square tests showed no significant differences in age (p=0.596) and gender (p=1.000) distribution of the two groups.

2.3.1. Familiarization task

Children individually watched a video with the instructions of the familiarization task. After this video, a researcher verbally repeated the instructions and answered any question children might have. For the familiarization task, children were requested to watch another video, which was designed to convey the idea of temporal description to children, without the use of food cues (Figure 1). The video showed circles of different colors, which appeared and disappeared at different points in time and they had to describe the sequence using either TCATA or TDS. Children were instructed to use a list of colors to describe all those they saw on the screen (TCATA) or the color that caught their attention (TDS) at each time.

Please insert Figure 1 around here

2.3.2. Sample tasting

Instructions were given for the sample tasting using a similar procedure (monkey character) to the familiarization task. Children received six milk dessert samples and they were asked to describe them using a TCATA or TDS task. Desserts (20 g) were served in black plastic cups coded with 3-digit random numbers at 8°C. They were presented following a Williams' Latin Square design to avoid order and carry over effects. Still mineral water was used for rinsing between samples. A warm-up sample was included to familiarize the children with the tasting protocol. The warm-up sample was equal to the 7% w/w added sugar dessert identified as “Sugar Reduced” in Table 1, but with a different vanilla.

Children were asked to carefully read the list of words before starting the test and to indicate if they had any doubt about their meaning. Attribute definitions were verbally provided if children expressed that their meaning was not clear. Then, they had to place a spoonful of sample in their mouths and immediately touch the “start” button in the screen to describe the sensory characteristics of samples using either TCATA or TDS. Children were instructed to eat the whole spoonful of sample at once and they were not allowed to taste it again. TCATA was performed as described by Castura et al. (2016). Children were instructed to check all the words that applied to describe what they perceived at each time while consuming the sample. They were free to select several attributes concurrently. If a word was no longer perceived, children had to uncheck it. For the TDS task children were instructed to select the word that described the sensation that catch their attention the most at a given time (Pineau et al., 2009).

Six words were included in the list for both methods: sweet, vanilla flavor, off-flavor, creamy, soft and hard. Attributes were selected based on results from previous studies (Alcaire et al., 2017; Ares, Giménez, Barreiro, & Gámbaro, 2010; Bruzzone et al., 2015) and pilot testing with children. The duration of the temporal evaluations was fixed at 40 s, based on pilot tasting. The recorded evaluation time was equal for all children (40 s), and a stopping button was not provided. Swallowing time was not recorded either.

After the dynamic sensory characterization task, children were asked to rate their overall liking using a 9-point hedonic scale (1=dislike very much and 9=like very much) with emoji anchors (😩=dislike very much and 😍=like very much). All categories in the scale were labeled with their corresponding numbers, while emojis were used only at the extreme anchors to avoid redundancy between similar looking emojis. The final version of the evaluation protocol was based on results of a pilot test with 4 children.

2.4. Data Analysis

All data analyses were performed using R software version 3.5.2 (R Core Team, 2018. For the dynamic sensory data, children who failed to select at least one attribute were excluded from the analysis: TCATA (n=1) and TDS (n=7).

2.4.1. Overall liking

Overall liking data were analyzed using a mixed linear model considering sample, temporal method and their interaction as fixed effects, and children as random effect. When significant differences were found, Fisher's test was used for post-hoc comparison of means. A significance level of 5% was considered.

Hierarchical cluster analysis considering Euclidean distance and Ward's method was applied on standardized overall liking data to explore segmentation. A linear mixed model was used to evaluate the existence of significant differences among samples within each cluster. In addition, the effect of the factors considered in the 2x2 experimental design on overall liking was of interest. In order to evaluate this, both for the whole sample of children and for each cluster, a mixed linear model was used on the overall liking data of the four samples formulated using the experimental design considering vanilla, starch and their interaction as fixed effects.

The identified groups were compared in terms of their gender distribution and the temporal method used to evaluate samples using chi-square test. In addition one-way ANOVA was used to compare the groups in terms of their age.

2.4.2. Analysis of TCATA data

The analysis was done with standardized time data (Lenfant, Loret, Pineau, Hartmann, & Martin, 2009), by taking into account the time from selection of the first attribute (time= 0%) to the end of the evaluation (time= 100%). The end of the evaluation was fixed for all participants, as data was always recorded until 40 s were reached.

TCATA curves were constructed for each sample as recommended by Castura et al. (2016). Citation proportions were calculated per attribute as the number of children that selected a term as applicable to describe a sample at each moment of the evaluation. TCATA curves were smoothed using a spline type polynomial. For each term and each pair of products, a sign test was used at each time point to evaluate the existence of significant differences in the citation proportions.

2.4.3. Analysis of TDS data

TDS curves were constructed using standard procedures (Cadena et al., 2014). Seven children were excluded from the analysis because they did not select any attribute for describing the sample. Time standardization was used as mentioned in 2.4.2. The attribute selected as dominant at each time of the evaluation was computed. The dominance rate for each attribute was calculated as the proportion of children that selected that attribute as dominant at each moment of the evaluation. The dominance rate for each attribute was smoothed using a spline type polynomial and plotted versus time to obtain TDS curves. Chance level and significance levels were calculated as suggested by Pineau et al. (2009). Significant differences between pairs of samples in the citation proportions of all attributes were evaluated using the sign-test.

3. Results

3.1. Overall liking

When data was analyzed considering the whole sample of children, no significant differences (p=0.14) among milk dessert samples were found in terms of their overall liking. As shown in Table 2, the average liking scores for all samples were close to 7 in the 9-point hedonic scale. This suggests that, on average, children showed a highly positive hedonic reaction to samples, regardless of their sugar content and concentration of vanilla and starch.

However, when only the data of the four sugar-reduced samples was analyzed, significant main effect of vanilla was found (Table 3). The increase of vanilla concentration lead to an increase in liking (Figure 2.a).

Please insert Table 2 around here

Please insert Table 3 around here

Please insert Figure 2 around here

Further exploration of the data using agglomerative hierarchical clustering analysis revealed the existence of segmentation based on the overall liking. Children were clustered into three groups, with clearly different liking patterns (Table 2). No significant differences between the clusters were found in their age (p=0.643) or the temporal method used for evaluating samples (p=0.368). However, a significant difference in the gender distribution of the samples was found (p=0.035). Cluster 1 and 3 were composed by a higher percentage of girls compared to Cluster 2 (63 % and 78% vs 43%).

Children in Cluster 1 (n = 24) gave the lowest overall liking score to the sample formulated with the highest concentration of vanilla and starch (SR.Vanilla+Starch), followed by the Sugar Reduced sample (Table 2). The linear mixed model performed on the overall liking data of the four samples of the design of experiments revealed a significant interaction effect between vanilla and starch (Table 3). As shown in Figure 2b increasing vanilla concentration (by adding vanilla B) led to an increase in liking at low starch concentration, whereas the opposite effect was observed at high starch concentrations.

For children in Cluster 2 (n = 70), the sample formulated with the increase of vanilla and starch (SR.Vanilla+Starch) did not significantly differ from the control sample. All the other samples showed a significantly lower overall liking score (Table 2). According to the design of experiment, only the main effect of vanilla B showed a significant effect on overall liking of the sugar reduced samples (Table 3). As shown in Figure 2c increasing the vanilla B concentration led to an increase in liking. The effect of starch was marginal (p=0.053). For children in this cluster, samples with higher starch concentration tended to have higher liking scores.

Children in Cluster 3 (n = 18) gave the lowest overall liking score to the control sample, whereas the sugar-reduced sample showed the lowest overall liking score among the four samples included in the experimental design (Table 2). In this case, linear mixed model focused on the experimental design was not able to identify any significant effect (Table 3). However, vanilla B concentration had a marginal effect (p=0.062). Children in Cluster 3 tended to give higher liking scores to the samples with more vanilla.

3.2. Temporal evaluation using TCATA

Figure 3 shows the TCATA curves for the five evaluated samples. The citation proportion of the attributes increased rapidly at the beginning of the evaluation, mostly in the first quarter. Later, only modest changes were observed, which suggests that children rarely unchecked the attributes or selected new ones. The terms *creamy, sweet* and *vanilla flavor* showed the highest citation proportions for all samples, whereas the term *hard* always showed citation proportions lower than 0.1. As shown in Figure 3a, the Control sample was mainly characterized by a high citation proportion of the terms *sweet* and *creamy* over the whole evaluation period. *Vanilla flavor* and *soft* showed maximum citation proportions close to 0.60 around in the first fifth of the evaluation period and then slightly decreased.

Compared to the Control, all samples except for SR.Vanilla+Starch showed significantly lower citation proportions for the term *swee*t at some point of the evaluation (Table 4). The SR.Vanilla sample also differed from the Control in the citation proportion of the term *vanilla flavor*, whereas the SR.Starch sample showed a higher citation proportion of the term *off-flavor* during a small period of time and a lower citation proportion of the term *soft* for a considerable part of the evaluation (Table 4). Finally, the sample with increase of starch and vanilla did not significantly differ from the Control sample in any sensory attribute (Table 4).

Small differences between the other pairs of samples were found. No significant differences between the sugar-reduced samples were found in the citation proportions of the terms *sweet* and *vanilla flavor*. Differences were only found for the attributes *off-flavor*, *creamy* and *soft*. The Sugar Reduced sample showed a lower citation proportion of the term *creamy* for a considerable part of the evaluation compared to the samples with higher starch concentration: SR.Starch and SR.Vanilla+Starch. In addition, the Sugar Reduced sample showed a significantly higher citation proportion of the term *soft* than the SR.Starch sample. Meanwhile, the SR.Starch sample showed a higher citation proportion of the term *off-flavor* compared to the SR.Vanilla+Starch sample for a short period of time, as well as a lower proportion citation of the term *soft*.

Please insert Figure 3 around here

Please insert Table 4 around here

3.3. Temporal evaluation using TDS

The TDS task was not able to capture the temporal evolution of the attributes for most of the samples. As shown in Figure 4, the curves were mostly flat, suggesting that most children selected only one attribute during the whole evaluation. In addition, the citation proportions of all the attributes were lower than 0.35 for all samples. For this reason, few attributes were found to be significantly dominant.

The control sample was characterized by the dominance of the term *sweet* during the majority of the evaluation period and by the dominance of *creamy* at the beginning of the evaluation. In addition, *off-flavor* was on the limit of dominance in the first half of the evaluation time (Figure 3).

The TDS curve of the reduced sample showed that *off-flavor* and *creamy* were dominant but only at the beginning of the evaluation. In the case of the SR.Vanilla sample, none of the attributes reached significance. The SR.Starch sample was only characterized by the dominance of *creamy*, whereas in the case of the SR.Vanilla+Starch sample, the terms *creamy* and *sweet* were significantly dominant during most of the evaluation period.

Differences in the citation proportions of all attributes between pairs of samples were small, as shown in Table 5. In terms of sweetness, only the sample SR.Vanilla+Starch showed a difference from the control at some point of the evaluation time (Table 5). The Sugar Reduced and SR.Vanilla samples showed a lower citation proportions of the term *soft* compared to the Control, however the last one only showed this difference for a small period of time. The SR.Vanilla sample also had a higher citation proportion of the term *vanilla flavor.* No significant differences between the SR.Starch sample and the control sample were found.

Regarding differences among the sugar-reduced samples (Table 5), the SR.Vanilla sample showed a higher citation proportion of the term *vanilla flavor* than the Sugar Reduced and SR.Starch samples, which lasted for the longest period of time, whereas it showed a lower citation proportion of the term *off-flavor* than the SR.Starch sample. This last sample also showed a higher citation of the term *off-flavor* than the SR.Vanilla+Starch sample, though this difference was observed for a smaller period of time. In addition, a difference in the citation proportion of the term *soft* was also found for this pair, the SR.Starch sample was less *soft*. Finally, a difference in the citation proportion of the term *hard* was observed between the SR.Vanilla and SR.Vanilla+Starch samples but it was brief and small.

Please insert Figure 4 around here

Please insert Table 5 around here

4. Discussion

Results from the present work showed that a reduction up to 40% of added sugar had no relevant effect in children's hedonic reaction and only minor effects on sensory perception. On average, children liked the straight sugar reduced sample as much as the bench mark sample, though the impact on the dynamics of sensory perception is less clear. This suggests that there is room for reducing the sugar content of this type of product without affecting liking, and, at first glance, with no need of compensation strategies. Other studies have shown that the sweetness of commercial products available in the marketplace is usually higher than consumers' preferred sweetness level (Chollet, Gille, Schmid, Walther, & Piccinali, 2013; Reed, Mainland, & Arayata, 2019). The feasibility of reducing the sugar content of dairy products has also been reported by other authors (Harwood, Loquasto, Roberts, Ziegler, & Hayes, 2013; Li, Lopetcharat, Qiu, & Drake, 2015). Still, the conclusion reached when analyzing results for the whole sample of children should be taken with care, as subtle but significant differences among samples' sensory profiles were found, as well as individual differences in children's liking patterns.

4.1. Cross-modal interactions for reducing the sugar content of products targeted at children

In the present work, sugar reduction mainly impacted the texture and sweet taste of the milk desserts, which fits expectations (Chollet et al., 2013; Goldfein & Slavin, 2015;

Pineli et al., 2016). Aroma/texture/taste interactions can be used to counteract these changes and achieve larger sugar reductions in shorter periods of time (Alcaire et al., 2017; Oliveira et al., 2015; Thomas-Danguin et al., 2016).

Results from the present work showed that increasing the concentration of vanilla aroma lead to an enhancement of vanilla flavor perception. An increase in sweetness was detected in a paired comparison with trained assessors, in agreement with previous studies (Labbe et al., 2006; Oliveira et al., 2015). Although most of the children tended to increase their liking with increasing vanilla concentration, results from the dynamic sensory methods did not show differences in sweetness. The discrepancy between trained assessors and the dynamic sensory methods with the children could be explained by the fact that cross-modal interactions between vanilla aroma and sweet taste are expected to be small in real food (Wang, Hayes, Ziegler, Roberts, & Hopfer, 2018), which could have prevented the identification of significant differences in a dynamic sensory characterization task with children. In addition, children have been reported to be unlikely to attend to only one attribute (James, Laing, Oram, & Hutchinson, 1999; Popper & Kroll, 2011), which may make it hard to find differences in several attributes at the same time. Still the enhancement of sweetness with vanilla cannot be ruled out, though dynamic sensory methods did not show this effect. Another method focused on attribute intensity may have led to a different result.

The increase of starch impacted texture attributes, as expected. The increase in starch concentration led to an increase in creaminess and a decrease in perceived thickness (evaluated using the terms *soft* and *hard*), in agreement with previous studies (de Wijk, Terpstra, Janssen, & Prinz, 2006; de Wijk, van Gemert, Terpstra, & Wilkinson, 2003). According to De Wijk et al. (2003), the addition of starch decreased the sweetness perception due to a possible interference with the diffusion of taste compounds. However, Kanemaru et al. (2002) reported that the addition of starch could increase sweetness due to molecular interaction with sugar. In the present study, the increase in starch concentration did not seem to modify flavor perception.

The combined increase of vanilla and starch concentration minimized the sensory changes caused by sugar reduction, probably due to an increase in sweetness perception. The SR.Vanilla+Starch sample was the only sugar-reduced sample for which sweet was significantly dominant in the TDS task. This is in line with the findings reported by Alcaire et al. (2017), who found that the increase of vanilla aroma and starch increased the sweetness perception and reduced the changes in liking for sugar reduced milk desserts among adults. Although the sweetness enhancement due to the increase of vanilla was modest, its effect may have been boosted by the increment of starch due to its role in facilitating the release of volatiles from the matrix (Arancibia, Jublot, Costell, & Bayarri, 2011; González-Tomás et al., 2007). Also, it is possible that a perceptual interaction took place: the boost of creaminess and vanilla flavor could have triggered an overall sensory experience closer to a regular product.

4.2. *Heterogeneity in children's reaction to cross-modal interactions*

Careful interpretation of the impact of sugar reduction should be paid since it is known that food preferences in children are influenced by multiple genetic and environmental factors (Wardle & Cooke, 2008). This leads to individual differences in food preference and choice, which are likely to influence success of sugar reduction strategies. Despite the majority of children liked all the samples, three groups were identified with distinctive liking patterns.

One small group tended to strongly dislike the sample with the highest concentration of sugar which was highly liked by the rest of the children. Differences in sweet preferences among children have been identified due to early experiences, genetic variances and cultural components (Liem & Mennella, 2002; Mennella, Pepino, Yanina, and Reed, 2006; Pepino & Mennella, 2005). For instance, the existence of sweet dislikers among children has been reported by Garneau, Nuessle, Mendelsberg, Shepard, & Tucker (2018). These authors reported that, in contrast to showing a greater preference for high sweetness levels, their liking decreased as the concentration of sucrose increased.

Considering that the aim of product reformulation is to at least maintain liking of the control sample, it is interesting to note that added sugar reduction of around 40% led to maintained or increased liking for 37.5% of the children (Clusters 1 and 3), while for the remaining 62.5% (Cluster 2) liking decreased but could be restored by the addition of high starch and vanilla levels. Another relevant point is that, even though around 80% of the children gave the highest overall liking to the dessert formulated with the highest levels of vanilla and starch, one group of children showed a strong dislike for this sample.

Although the findings regarding individual differences were interesting, it is important to take into account that the number of children in each cluster was small. Future studies should be conducted with a larger consumer sample to confirm the trends found here. In addition, whether the individual differences found in hedonic perception are due to differences in sensory perception, or if they are just the result of differences in children's preference patterns, deserves further investigation.

Individual differences could also be related to the nutritional status of children. In this sense, Proserpio et al. (2016) showed that certain aromas had a higher impact on the sensory perception of obese adult woman than normal weight ones. Although in the present study data on children's body mass index was not collected, this information could be valuable for future research.

4.3. Methodological considerations

The present study is the first to report the use of dynamic sensory methods with children. Although children reported to understand both methods and were able to complete the tasks, results showed that children mostly used the methods as static. As shown in Figure 4, TDS curves were mostly flat, suggesting that children tended to select only one attribute during the whole evaluation period. In the case of TCATA, although Figure 3 showed larger variability of citation proportions over time, children tendency to unselect attributes was limited. This tendency, although less pronounced, has been reported with adults, both trained and untrained (Ares et al., 2015; Castura et al., 2016). Future studies should evaluate if the implementation of a fading variant could improve children's performance in dynamic sensory characterization tasks. In this approach, terms are automatically de-selected after a fixed period of time and assessors are asked to select them again if they are still applicable. Ares et al. (2016) reported that TCATA and its fading variant showed similar results in eight studies with trained assessors and consumers, but the fading variant may result in a more accurate dynamic profile and higher discriminability.

Alternatively, van Bommel, Stieger, Schlich & Jager (2019) recently introduced a hold-down variant for temporal dominance methodologies as a way to capture non dominance periods. In this methodology, participants actively hold down the button of the attribute that is perceived dominant and release it when it is no longer perceived. Although the authors reported that this variant did not outperform the classic methods with adults, it might improve children's performance since it could keep their attention for longer, as participants are more actively involved during the evaluation. Moreover, it might help to eliminate false dominance periods at the end of the mastication period or due to hesitation.

In addition, it could be interesting to evaluate the application of dynamic sensory methods with solid products that undergo larger changes in their sensory characteristics throughout consumption. The fact that most variation in TCATA curves occurred in the first fifth or quarter of the evaluation period also suggest that children tended to use this method as static: once attributes were selected no further changes were registered.

Despite the limited changes observed throughout consumption, the sensory profiles of the evaluated samples fitted expectations. The terms with the highest citation proportion were similar to those reported in previous studies dealing with the same product category (Ares et al., 2010; Bruzzone et al., 2015; René A. de Wijk et al., 2003; Vidal, Barreiro, Gómez, Ares, & Giménez, 2013). In addition, significant differences among samples that fitted expectations were identified. These results point towards children's ability to describe the sensory characteristics of products, in agreement with previous studies (Laureati et al., 2017; Schouteten, De Steur, Lagast, De Pelsmaeker, & Gellynck, 2017; Verwaeren, Gellynck, Lagast, & Schouteten, 2019).

Regarding the comparison of TCATA and TDS, both methodologies showed similar results regarding the most salient sensory characteristics of the samples and differences among them. Similar results have been reported with adult assessors (Ares et al., 2016). As expected, the main difference between the methods was related to the citation proportion of the individual attributes. In particular, the low dominance rates of all the attributes in TDS points towards heterogeneity in how children selected the sensory attribute that caught their attention. In this sense, further exploration of children's understanding of the concept of dominance is warranted.

Another methodological consideration of this study is the sugar reduction level that was used. Although ~ 40% reduction in added sugar led to a decrease in overall liking for the majority of the children, the sugar reduced sample was not disliked. Future studies should consider higher reduction levels in order to achieve children's' rejection of the reformulated product, in which compensation strategies such as cross-modal interaction would be more relevant to achieve reformulation goals.

5. Conclusions

Results from the present work suggest that it is feasible to reduce the added sugar concentration in vanilla milk desserts without largely affecting children's hedonic perception. The use of cross-modal interactions based on vanilla flavor and texture modification was effective at minimizing the changes in the sensory characteristics of samples caused by sugar reduction. This strategy should be implemented in the context of gradual sugar reduction programs in order to achieve a long-term reduction in children's preference for products with high sweetness intensity.

Large heterogeneity was found in how children reacted to the changes in the sensory characteristics of samples caused by the increase in the concentration of vanilla and starch. Future research should be conducted to further understand the factors responsible for individual differences in children's reaction to cross-modal interactions in sugar-reduced milk products.

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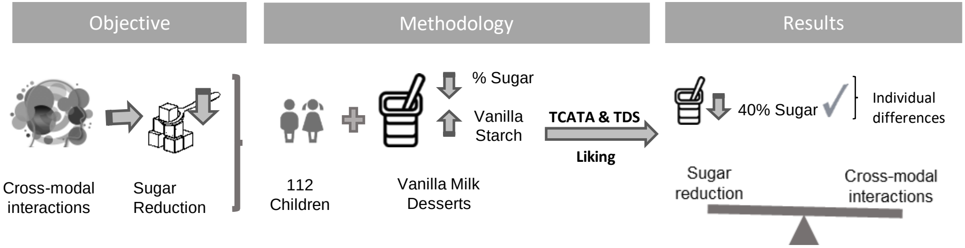
Objective
Methodology
Results
Cross-modal interactions
Sugar Reduction
112 Children
Vanilla Milk Desserts
% Sugar
Vanilla Starch
TCATA & TDS
Liking
40% Sugar
Individual differences
Sugar reduction
Cross-modal interactions

Highlights

- A sugar reduction up to 40% is feasible in vanilla milk desserts for children
- Cross-modal interactions minimized the sensory changes in sugar-reduced samples.
- Individual differences in children's hedonic perception were found

Table 1. Sugar, starch and vanilla concentrations of the samples included in the study.

Sample(*)	Total Sugar (%) (**)	Added sugar (%)	Starch (%)	Vanilla A (%) (***)	Vanilla B (%) (***)
Control	16	12	4.3	0.4	-
Sugar Reduced	11	7	4.3	0.4	-
SR.Vanilla	11	7	4.3	0.4	0.2
SR.Starch	11	7	4.7	0.4	-
SR.Vanilla+Starch	11	7	4.7	0.4	0.2

(*) SR stands for sugar-reduced sample.

(**) Sugar corresponding to lactose in milk plus added sugar

(***) Vanilla A and B correspond to different flavorings. Supplementary Table 1 shows the volatile profile of the two flavorings.

Table 2. Average overall liking scores (and standard error) for the evaluated samples for the whole sample and the three clusters identified in the Hierarchical cluster analysis.

Sample (*)	Whole sample (n=112)	Cluster 1 (n=24)	Cluster 2 (n=70)	Cluster 3 (n=18)
Control	7.2 ± 0.2 a	7.6 ± 0.3 b,c	7.9 ± 0.2 b	3.7 ± 0.5 a
Sugar Reduced	6.8 ± 0.2 a	6.8 ± 0.5 b	6.9 ± 0.3 a	6.2 ± 0.6 b
SR.Vanilla	7.4 ± 0.2 a	7.9 ± 0.3 c	7.3 ± 0.2 a	6.9 ± 0.6 b,c
SR.Starch	7.0 ± 0.2 a	7.0 ± 0.5 b,c	7.1 ± 0.3 a	6.8 ± 0.6 b,c
SR.Vanilla+Starch	7.1 ± 0.2 a	4.5 ± 0.4 a	7.8 ± 0.2 b	7.8 ± 0.3 c

(*) SR stands for sugar-reduced sample.

Sample descriptions are provided in Table 1. Overall liking scores were evaluated using a 9-point hedonic scale. Average values with different letters within a column are significantly different according to Fisher’s test ($p < 0.05$).

Table 3. Results (p-value) of the mixed linear model testing the effect of vanilla, starch and their interaction on the overall liking of milk desserts formulated using an experimental design for the whole sample and for the clusters identified in the hierarchical cluster analysis.

Effect	Whole sample (n=112)	Cluster 1 (n=24)	Cluster 2 (n=70)	Cluster 3 (n=18)
Vanilla	0.028*	0.014*	<0.001***	0.062
Starch	0.862	<0.001***	0.053	0.104
Vanilla:Starch	0.105	<0.001***	0.251	0.800

Note: Significant effects are shown with *: * $p < 0.05$, *** $p < 0.001$.

Table 4. Average difference in citation proportions (± standard deviation) and time periods at which these occur for pairs of samples showing significant differences in TCATA curves. Only differences significant at a significance level of 5% are shown.

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Attribute & Sample Pair (*)	Citation proportion difference (**)	Time periods
Sweet		
Control vs. Sugar Reduced	0.19 ± 0.01	0-4, 83-85, 100
Control vs SR.Vanilla	0.20 ± 0.01	83-100
Control vs. SR.Starch	0.21 ± 0.01	7-11
Vanilla flavor		
Control vs SR.Vanilla	-0.19 ± 0.01	49, 52-54, 58-63, 65-72, 78-84
Off-flavor		
Control vs. SR.Starch	-0.18 ± 0.01	7-11
Starch vs. SR.Vanilla+Starch	0.21 ± 0.02	3-8
Creamy		
Sugar Reduced vs. SR.Starch	-0.17 ± 0.001	64-100
Sugar Reduced vs SR.Vanilla+Starch	-0.17 ± 0.001	69-100
Soft		
Control vs. SR.Starch	0.20 ± 0.01	19-21, 69-74,76, 84-100
Sugar Reduced vs. SR.Starch	0.13 ± 0.001	93-100
SR.Starch vs. SR.Vanilla+Starch	-0.16 ± 0.04	0-2, 4-5, 95-99

(*) SR stands for sugar-reduced sample.

(**) The citation proportion differences were calculated by averaging the differences in citation proportion between pairs of samples across all the time periods showing a significant difference ($p<0.05$) when their TCATA curves were compared.

Table 5. Average difference in citation proportions (± standard deviation) and time periods at which these occur for pairs of samples showing significant differences in TDS curves. Only differences significant at a significance level of 5% are shown.

Attribute & Sample Pair (*)	Citation proportion difference (**)	Time periods
Sweet		
Control vs. SR.Vanilla+Starch	0.19 ± 0.003	83-86, 100
Vanilla flavor		
Control vs SR.Vanilla	-0.15 ± 0.002	16-18
Sugar Reduced vs SR.Vanilla	-0.20 ± 0.01	50-59, 70, 72-80, 82-83
SR.Vanilla vs SR.Starch	0.22 ± 0.02	22-72
Off-flavor		
SR.Vanilla vs. SR.Starch	-0.20 ± 0.02	4-17
SR.Starch vs. SR.Vanilla+Starch	0.21 ± 0.02	3-8
Soft		
Control vs. Sugar Reduced	-0.13 ± 0.01	0-29
Control vs. SR.Vanilla	-0.11 ± 0.002	0-3
SR.Starch vs. SR.Vanilla+Starch	-0.16 ± 0.04	0-5, 95-99
Hard		
SR.Vanilla vs. SR.Vanilla+Starch	0.08 ± 0.00	0-3

(*) SR stands for sugar-reduced sample.

(**) The citation proportion differences were calculated by averaging the differences in citation proportion between pairs of samples across all the time periods showing a significant difference ($p<0.05$) when their TDS curves were compared.

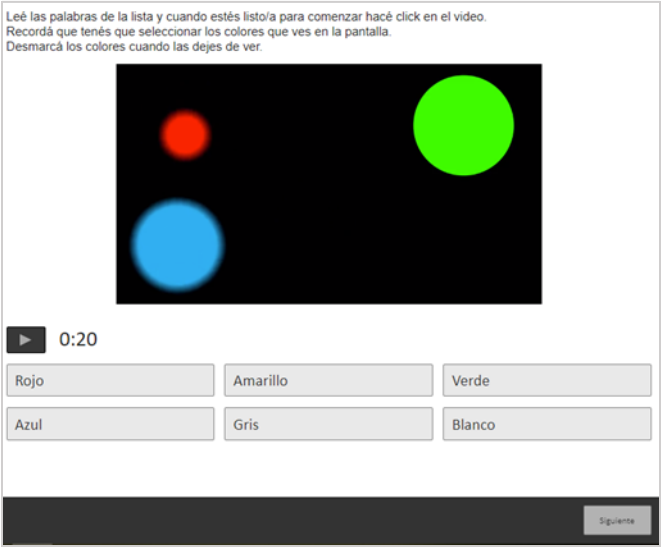

Figure 1. Example video shown in the familiarization task

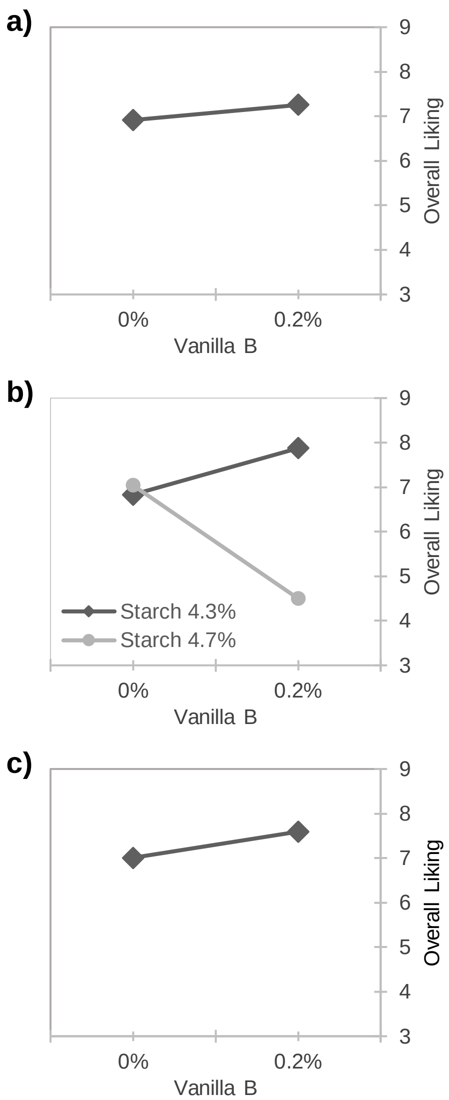

Figure 2. Significant effects of the factors of the experimental design for: a) the whole sample (n=112), b) Cluster 1 (n=24), and c) Cluster 2 (n=70).

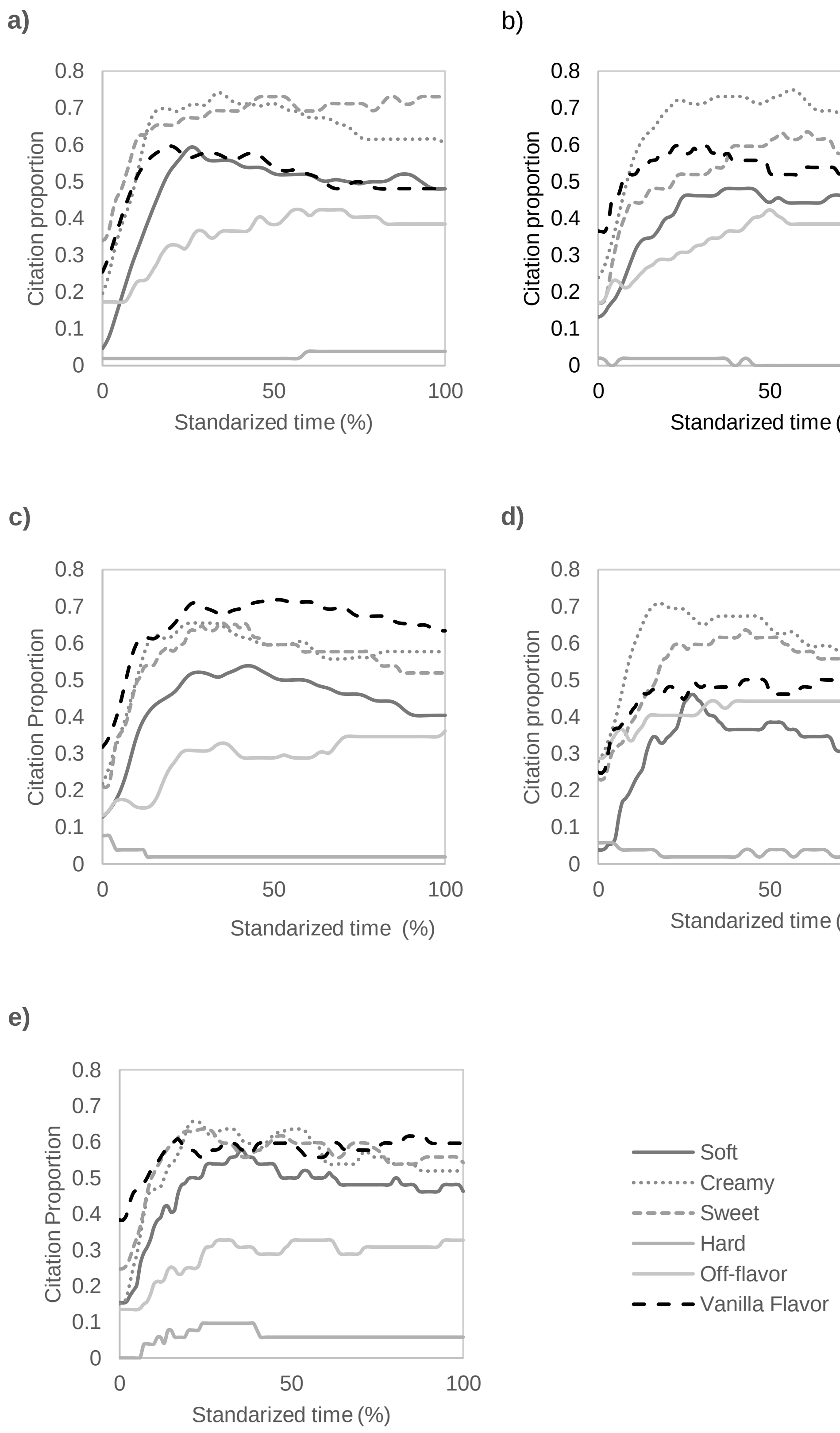

Figure 3. Temporal check-all-that-apply curves for five vanilla milk dessert samples: A) control, B) Sugar Reduced, C) SR.Vanilla, D) SR.Starch and E) SR.Vanilla+Starch. SR stands for sugar-reduced sample. The description of the samples is provided in Table 1.

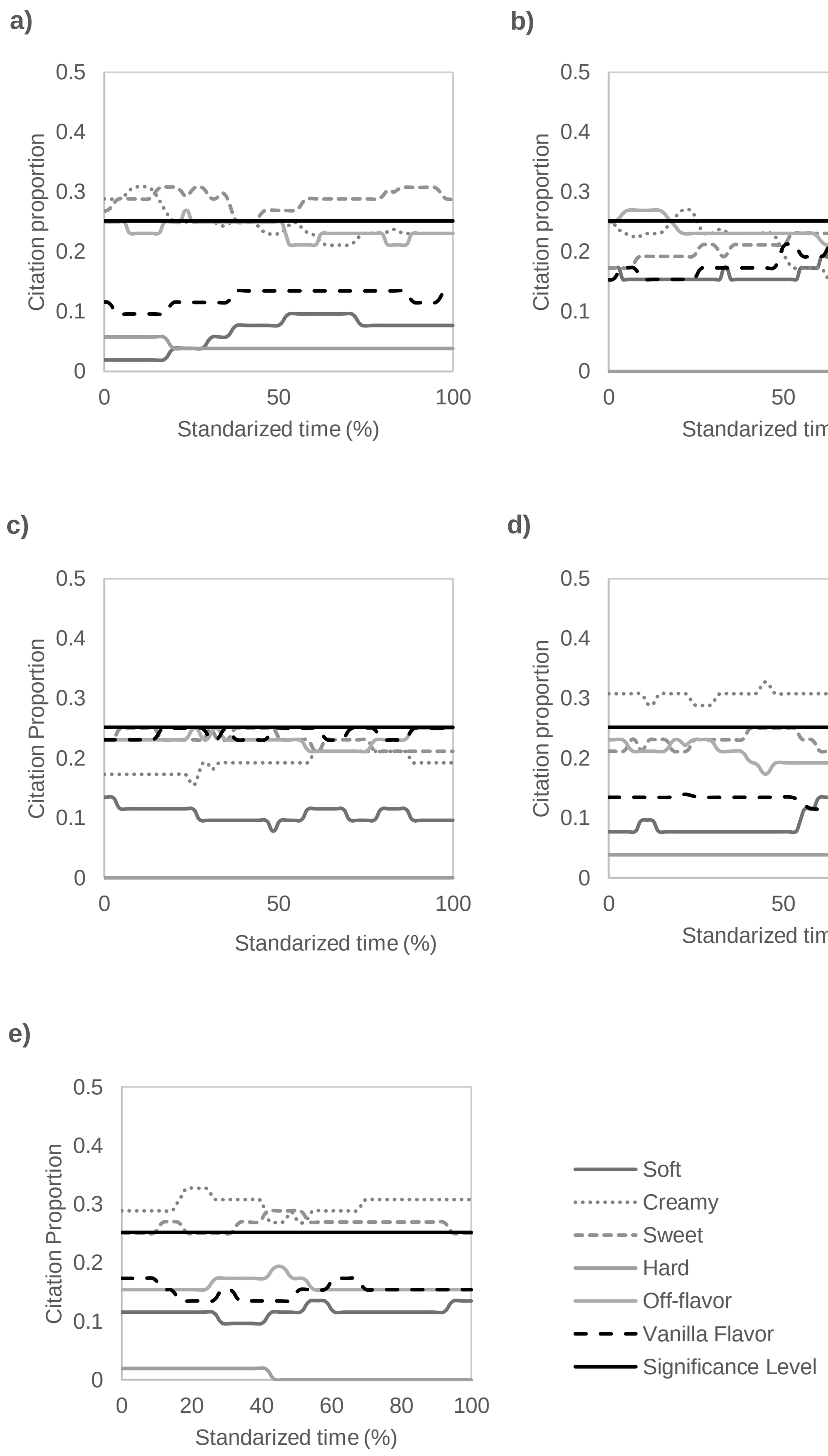

Figure 4. TDS smooth curves for five dessert samples: A) Control, B) Sugar Reduced, C) SR.Vanilla, D) SR.Starch and E) SR.Vanilla+Starch. SR stands for sugar-reduced sample.