



Linking oral processing behavior to bolus properties and dynamic sensory perception of processed cheeses with bell pepper pieces

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ABSTRACT

The addition of food particles to food matrices is a convenient approach that allows to steer oral behavior, sensory perception and satiation. The aim of this study was to determine the influence of physical-chemical properties of heterogeneous foods on oral processing behavior, bolus properties and dynamic sensory perception. Bell pepper gel pieces varying in fracture stress and concentration were added to processed cream cheese matrices differing in texture. Addition of bell pepper gel pieces to processed cheeses increased consumption time, decreased eating rate and led to harder and less adhesive bolus with more saliva incorporated. Addition of bell pepper gel pieces to processed cheeses decreased dominance rate and duration of creaminess, smoothness, melting and dairy flavor and increased graininess and bell pepper flavor. Increasing fracture stress of bell pepper gel pieces from 100 to 300 kPa resulted in longer consumption time and lower eating rate. For hard/non-adhesive processed cheese matrices increasing gel pieces fracture stress lead to a bolus with larger particles and more saliva. These changes were accompanied by decreased dominance perception of creaminess and bell pepper flavor and increased dominance of graininess. Increasing the concentration of bell pepper gel pieces from 15 to 30% did not affect oral behavior but led to the formation of harder and less adhesive bolus with larger particles and less saliva that were perceived with reduced dominance of creaminess, meltiness and dairy flavor while dominance of graininess and bell pepper flavor increased. Changing the texture of the cheese matrix from soft/adhesive to hard/non-adhesive decreased consumption time, increased eating rate, did not influence bolus properties and decreased dominance rate of creaminess, smoothness and melting sensations. Number of chews and total consumption time were positively correlated with saliva content of the bolus, number of bolus particles, bolus hardness, dominance of firmness, chewiness and graininess. We conclude that the modification of physical-chemical properties of processed cheeses and embedded bell pepper gel pieces can be a strategy to steer oral behavior and bolus properties which consequently determine dynamic sensory perception.

1. Introduction

Throughout oral processing the bolus structure changes continuously as a result of food comminution, hydration and agglomeration (Witt & Stokes, 2015). These changes in bolus structure during oral processing cause dynamic changes in sensory perception and ultimately determine food liking (Koç, Vinyard, Essick, & Foegeding, 2013). A detailed mechanistic understanding of how structural transitions of food bolus are perceived, so how structural transitions contribute to sensory

properties, is still missing. It is important to understand how oral processing behavior, bolus properties and sensory perception change depending on structural and physical-chemical properties of foods. Based on this understanding foods with specific properties might be designed with enhanced eating experiences.

Numerous studies demonstrated that consumers adapt oral behavior to the texture and mechanical properties of homogeneous foods. Positive relationships have been reported between viscosity of a broad range of liquid and semi-solid foods and consumption time. For a broad range of

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solid foods, consumption time and number of chews have been positively correlated with mechanical food properties such as fracture stress, fracture strain and other food texture properties (Agrawal, Lucas, Bruce, & Prinz, 1998; Aguayo-Mendoza et al., 2019; Çakir et al., 2012; Doyennette, Aguayo-Mendoza, Williamson, Martins, & Stieger, 2019; Engelen, Fontijn-Tekamp, & Bilt, 2005; Foster, Woda, & Peyron, 2006; Hiiemae et al., 1996; Koç et al., 2014; 2019; Kohyama, Gao, Ishihara, Funami, & Nishinari, 2016; Mioche, Bourdiol, & Monier, 2003; Peyron, Lassauzay, & Woda, 2002). Altering texture and mechanical properties of foods not only changes oral behavior but also leads to changes in bolus properties. Bolus particles of hard foods are smaller compared to those of soft foods (Chen, Khandelwal, Liu, & Funami, 2013). Reduction of bolus particle size facilitates incorporation of saliva into the bolus often leading to an increase in bolus cohesiveness, holding bolus fragments together and enabling a safe swallow. During bolus formation structural changes can be continuously sensed by the consumer providing dynamics to texture and flavor perception. Thus, food structure can be modified to control mechanical, texture and physical-chemical properties which impact oral behavior and bolus properties, and consequently sensory perception (Devezeaux de Lavergne, Derks, Ketel, de Wijk, & Stieger, 2015).

The majority of studies so far focused on understanding relationships between structure and physical-chemical food properties and oral behavior, bolus properties and sensory perception of homogeneous foods. Limited knowledge is available about these relationships for heterogeneous foods. Here, heterogeneous foods refer to foods that are composed of two food components that differ considerably in texture or mechanical properties, like foods that are composed of a matrix in which particles are embedded, such as chocolates with nuts, yogurts with granola pieces and cheeses with pieces of herbs or vegetables. Although heterogeneous foods are commonly consumed, since the contrast in texture and flavor can lead to high palatability (Hyde & Witherly, 1993), the effect of food heterogeneity on oral behavior, bolus properties and sensory perception is less well documented. The first of only few studies done with heterogeneous solid foods investigated oral processing behavior and bolus properties of chocolate and gelatin gels with embedded peanuts differing in moisture content (Hutchings et al., 2011). The matrix in which peanuts were embedded was responsible for differences in oral behavior whereas moisture content of peanuts did not influence oral behavior. Differences in particle size distribution of bolus peanut fragments were explained by differences in peanut moisture content rather than matrix type. It is possible that the peanuts characteristics did not affect oral behavior because the contrast in mechanical properties between matrices and peanuts might not have been large enough. The study did not explore how addition of peanuts to chocolate and gelatin gels effects oral behavior since these matrices without peanuts were not investigated nor was sensory perception of the heterogeneous foods quantified. Several other studies focused on the effect of particle addition on sensory perception and liking of heterogeneous foods. The influence of size and fracture stress of κ -carrageenan particles added to model soups and protein-based model gels on sensory perception and hedonic responses has been described (Santagiuliana, Christaki, Piqueras-Fizman, Scholten, & Stieger, 2018). It was shown that sensory properties of soups can be optimized by addition of congruent and familiar particles such as carrot pieces that match consumer' expectations (Santagiuliana et al., 2019). These studies did not investigate how addition of particles to the matrix change oral behavior and consequently bolus properties and sensory perception, thus a comprehensive understanding of these relationships is lacking.

The addition of food particles to a food matrix is a convenient approach that allows to steer oral behavior, sensory perception and satiation of heterogeneous foods. This because the properties of the particles can be varied independently from properties of the matrix. Previously, it was demonstrated that oral behavior of yogurts can be modified considerably by addition of peach gel particles (Aguayo-Mendoza et al., 2020). The addition of peach gel particles to yogurt was

sufficient to double consumption time and number of chews and thereby decreasing eating rate up to 60%. Another study indicated that addition of lyophilized pineapple cubes to yogurts changed oral behavior by lengthening consumption time, leading to an increase of expected satiating capacity (Tarrega, Marcano, & Fiszman, 2016). Furthermore, Mosca et al. (2019) showed that decreasing the size of granola particles added to yogurts, decreased eating rate and *ad libitum* food intake. The differences in eating rate and *ad libitum* intake between yogurts containing many small and fewer large granola particles (constant weight concentration) were 5 g/min (7%) and 17 g (5%), respectively. These studies highlight that in liquid foods addition of solid food particles can largely modify oral processing behavior and consequently impact expected satiety and *ad libitum* food intake.

To summarize, a comprehensive understanding of the influence of particle addition to foods on the relationships between oral behavior, bolus properties and dynamic sensory perception is lacking. The aim of this study was to determine the influence of physical-chemical properties of processed cream cheeses with bell pepper gel pieces on oral processing behavior, bolus properties and dynamic sensory perception. We hypothesize that the magnitude of the difference in mechanical properties between processed cheese matrix and added particles determines oral behavior and bolus properties.

2. Materials and methods

2.1. Samples

Eight processed cream cheeses with bell pepper gel pieces were prepared following a 2x2x2 full factorial design. Two processed cream cheeses varying in texture were prepared (soft/adhesive and hard/non-adhesive). Bell pepper gel pieces differing in fracture stress (low and high) were added at different concentrations (low and high) to processed cream cheeses. In addition, two processed cream cheeses without bell pepper gel pieces were prepared.

Processed cream cheese (Kiri®) was provided by Bel Group (Fromageries Bel, Suresnes, France), κ -carrageenan (GENUGEL type CHP-2) and low acyl gellan gum (KELCOGEL® gellan gum) were purchased from CP Kelco (Rotterdam, The Netherlands). Food colorant (Paprika Oleoresin WS, E160c) was purchased from Holland Ingredients (Meppel, The Netherlands). Red bell peppers, salt, sunflower oil, white bread and sparkling water were purchased from a local supermarket. All ingredients were food grade and samples were prepared under food safe conditions.

Soft processed cream cheese matrix with high adhesiveness was prepared by placing 100 g of cream cheese into a vacuum sealed bag in a water bath at 65°C for 30 min to allow the cream cheese to melt. To obtain hard processed cream cheese matrix with low adhesiveness, 12.5 g of κ -carrageenan gel were added to the cream cheese and melt together. Molten soft and hard processed cream cheese were poured into a vessel kept at 65°C and manually mixed avoiding incorporation of air. The κ -carrageenan gel was prepared by dissolving κ -carrageenan with tap water at 2% (w/v) and then heated in a water bath at 90°C for 30 min under continuous stirring. This solution was placed in ice bath for 20 min to cool and set. Seven replicates of spreadability test were performed on each of the homogenous cheese matrices (Sa and Hn) using a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS) equipped with a 5 kg load cell and a 90° conical stainless steel probe of 26 mm diameter and 12 mm height of the conical trunk. Processed cream cheeses were placed in a stainless-steel cylindrical mold (30 mm internal diameter and 10 mm height) and the excess removed with a knife to obtain a flat surface. The sample was placed in the fridge at 5 °C for 10 min. After that, cheeses were penetrated at 0.5 mm/s to a target depth of 9 mm. Then the probe was retracted from the cheese with a speed of 0.5 mm/s until the starting position was reached. Force (N) at maximum penetration depth (9 mm) was taken as a measure of hardness, and the energy (mJ) required to retract the probe (negative area under the

force–time curve) was taken as a measure of adhesiveness. Cheese hardness differed by a factor of 2x (soft, 6.9 ± 0.7 N; hard, 13.7 ± 0.5 N). Moreover, cheese adhesiveness differed by a factor 3x (non-adhesive 0.4 ± 0.05 mJ; adhesive 1.2 ± 0.1 mJ).

Bell pepper gel pieces varying in fracture stress (σ_F) were prepared following the methodology described by Santagiuliana et al. (2019). To give a more realistic bell pepper characteristics, two bell peppers concentrates were prepared. For the first concentrate, bell peppers were roasted for 13 min at 270°C in an oven and cooled down to room temperature. After removal of skin and seeds, bell peppers were pureed using a hand blender and then centrifuged (Allegra X-30R Centrifuge) for 15 min at 4500 rpm. The supernatant was sieved ($64\ \mu\text{m}$ mesh size) and stored at -18°C . For the second concentrate, bell peppers were cut, deseeded, juiced and reduced to 66% of its initial weight by heating in a stove. The concentrate was sieved ($64\ \mu\text{m}$ mesh size) and cooled down in an ice bath for 20 min and stored at -18°C . 50:50 (v/v) solutions of both concentrates were mixed with 0.5% colorant (E160c paprika oleoresin), 0.2% salt and either 1.5 or 3.6% low acyl gellan gum (Kelcogel F) to obtain soft and hard gel pieces (target fracture stress σ_F : 100 and 300 kPa, respectively). Solutions were placed in a water bath at 95°C for 45 min under continuous stirring which then were poured in either 500 ml squared plastic containers and placed in an ice bath for 20 min to cool and set, then gels were cut into cubes of $4 \times 4 \times 4$ mm. To characterize fracture behavior of gels, cylindrical samples were prepared in 30 ml syringes (Terumo, Leuven, Belgium) and cut with a diameter of 23 mm and height of 15 mm. A Texture Analyzer (TA.XT.plus, Stable Micro Systems-SMS) equipped with a load cell of 50 kg and a compression plate of 100 mm diameter was used to perform uniaxial compression tests on the bell pepper gels (-So and -Ha). Four replicates per sample were measured at 20°C at constant compression speed of 1 mm/s up to a strain of 30%. Average true fracture stress (kPa) and true fracture strain were calculated. Low and high fracture stress gels exhibited a true fracture stress of 106 ± 1 kPa and 295 ± 11 kPa and a true fracture strain (-) of 0.13 ± 0.01 and 0.14 ± 0.01 , respectively.

To produce heterogeneous cheeses, bell pepper gel pieces were added at 15% or 30% (w/w) to either soft/adhesive or hard/non-adhesive molten cream cheeses. The mixture was subsequently poured into a squared petri dish coated with a thin layer of sunflower oil and stored in a fridge at 4°C for 16–18 h. Cheeses were removed from petri dishes and cut into 5 g cubes ($20 \times 20 \times 12$ mm) with a custom-made

cutting frame. Cheese cubes were stored at 4°C for further use during oral behavior and sensory evaluations. Table 1 provides a summary description of all samples.

2.2. Participants

Thirty-four participants (11 male / 23 females) with an average age of 23 ± 3 years were recruited via social media and printed advertisements at Wageningen University. Inclusion criteria were Caucasian Europeans, age between 18 and 30 years, BMI ($18.5\text{--}25\ \text{kg/m}^2$), good general health and full denture. Exclusion criteria were dental braces, mouth piercings, use of medication, food allergies or intolerances, pregnancy, breastfeeding and smoking. Before taking part in the study, all participants signed an informed consent form. After completion of the study participants received a financial reimbursement.

2.3. Oral behavior characterization

Oral behavior was characterized by video recording the participants while consuming the cheeses as previously described by Aguayo-Mendoza et al. (2019) and Ketel et al. (2019). In short, to track oral movements, four round stickers were placed on the participant's face, two on the forehead spaced horizontally 5 cm, one on the tip of the nose, and one on the center of the chin. Participants were seated in a chair in front of a table with a video camera (Canon IXUS-500HS), approximately 50 cm from the participant's face. Videos were recorded, in a well-lit room, isolated from external noise or any other distractions. Cheese cubes ($20 \times 20 \times 12$ mm; 5 g) were served on a spoon and subjects were instructed to consume the samples as they would normally do, while being video recorded. Subjects were instructed to indicate every moment of swallowing by raising their hand. All 10 cheeses were presented in a randomized order and in monadic sequence at a serving temperature of 8°C and consumed over two test sessions of 60 min each. Videos were analyzed using Kinovea software (version 0.8.15). The parameters extracted from the videos were consumption time (s), number of chews, number of swallows, and eating rate (g/min).

2.4. Bolus collection and analyses at moment of swallowing

Boli of all participants were collected during six sessions of 30 min each. Participants were asked to chew every sample as they would normally do and expectorate the bolus when the alarm of the timer went off. The alarm was set at the average consumption for each cheese. The average consumption time of a given sample was calculated from the consumption time of all participants chewing the same cheese type during the oral behavior session explained in section 2.3. This procedure was followed to minimize the effect of inter-individual differences in oral behavior on bolus properties of the cheeses. In all sessions, participants received samples in a monadic sequence and in randomized order.

2.4.1. Particle size and number of bell pepper gel pieces in expectorated bolus

Expectorated bolus of the 8 heterogeneous cheeses were collected in a 120 ml cup. To gather particles that might be left in the mouth, participants took a sip of water and expectorate it in the same cup. Gel fragments in bolus were separated from the cheese matrix by rinsing the bolus for one minute under running lukewarm water and then dried with cold air and gently spread in a plastic petri dish ($120 \times 120 \times 17$ mm, Greiner Bio). Petri dishes were scanned (CanonScan 9000F markII) to obtain images in greyscale (8 bit) with a resolution of 1200 dpi. The images were analyzed using ImageJ software (National Institutes of Health, Version 1.51). The total number of particles and their median diameter (d_{50}) were quantified.

Table 1

Description of samples. First two letters of the sample codes indicate cheese matrix (Sa denotes soft/adhesive and Hn hard/non-adhesive), second two letters of the sample code indicate fracture stress of embedded bell pepper gel pieces (So denotes soft and Ha hard bell pepper gel pieces) and subscript numbers of the sample code indicate concentration of added bell pepper gel pieces (15 and 30% w/w for low and high, respectively).

Sample code	Description
Sa (-)	Soft/adhesive cheese without bell pepper gel pieces (reference)
Hn (-)	Hard/non-adhesive cheese without bell pepper gel pieces (reference)
SaSo ₁₅	Soft/adhesive cheese with soft bell pepper gel pieces embedded at 15%
SaSo ₃₀	Soft/adhesive cheese with soft bell pepper gel pieces embedded at 30%
SaHa ₁₅	Soft/adhesive cheese with hard bell pepper gel pieces embedded at 15%
SaHa ₃₀	Soft/adhesive cheese with hard bell pepper gel pieces embedded at 30%
HnSo ₁₅	Hard/non-adhesive cheese with soft bell pepper gel pieces embedded at 15%
HnSo ₃₀	Hard/non-adhesive cheese with soft bell pepper gel pieces embedded at 30%
HnHa ₁₅	Hard/non-adhesive cheese with hard bell pepper gel pieces embedded at 15%
HnHa ₃₀	Hard/non-adhesive cheese with hard bell pepper gel pieces embedded at 30%

2.4.2. Saliva incorporation in expectorated bolus

Boli from all 10 cheeses were directly expectorated in aluminium plates and immediately weight was determined. Boli samples were dried for 16 h at 105 °C in an atmospheric oven (Venti-line line, VWR®). After drying, samples were weighed. Dry matter of cheeses (DM_{sample}) and the dry matter of spit-out bolus (DM_{spit_bolus}) were determined and used to calculate saliva content of expectorated boli following the procedure described by Drago et al. (2011). The ratio of milligrams of saliva incorporated in the bolus per gram of food masticated (h_w) was calculated as:

$$h_w = \frac{DM_{sample} * 1000}{DM_{spit_bolus}} - 1000$$

2.4.3. Instrumental hardness and adhesiveness of expectorated bolus

Bolus from the 10 cheeses were collected in a cup in triplicate. Immediately after expectoration, the bolus was transferred to a stainless-steel cylindrical mold (30 mm internal diameter and 10 mm height). Then the bolus was gently pressed to avoid air incorporation and product above the mold's height was removed with a spatula to obtain a flat surface. The mold containing the bolus was fixed to the plate of the texture analyzer (TA.XT plus, Stable Micro Systems-SMS). The latter was equipped with a 5 kg load cell and a cylindrical aluminum probe of 20 mm diameter. The probe penetrated the bolus (back extrusion) with a test speed of 0.5 mm/s to a target distance of 9 mm, then the probe was retracted from the bolus at a speed of 0.5 mm/s until the starting position was reached. Force (N) at maximum penetration depth (9 mm) was taken as a measure of bolus hardness and energy (mJ) required to retract the probe (negative area under the force–time curve) was taken as a measure of bolus adhesiveness.

2.5. Sensory evaluation using temporal dominance of sensations

All 10 cheeses were evaluated by the $n = 34$ participants in duplicate using Temporal Dominance of Sensations (TDS). Before the evaluation sessions, participants underwent a familiarization session of 90 min where they were introduced to the TDS methodology, sensory attributes, definitions and the software used to collect their responses. Dominance was defined as: "Attribute that is catching the attention at a given time, not necessarily the attribute with the highest intensity". Attributes and definition were obtained from literature using similar foods (Santagiuliana et al., 2019) and by discussion between the researchers (Table 2). TDS data was collected over 3 sessions of 60 min each using EyeQuestion (Version 3.9.7, Logic 8 BV, Elst, The Netherlands). Participants were instructed to put the cheese cube in their mouth and simultaneously click the "start" button, then to select the attribute they perceived as dominant. Participants were instructed to click on a new dominant attribute each time that their perception changed; also that an attribute was considered as dominant until another attribute was

Table 2

Sensory attributes and definitions used during Temporal Dominance of Sensations analysis (TDS) of processed cream cheeses with and without bell pepper gel pieces.

Attribute	Definition
Creamy	Thick, velvety texture
Sticky	Adhesive sensation on tongue, palate and teeth
Firm	Amount of force required by the tongue to flatten the sample
Grainy	Perception of large irregularities in the sample. Mass of solid matter of no particular shape
Melty	Loss of structure in the mouth
Smooth	Uniform perception of the product during consumption
Chewy	The degree of elasticity of the sample
Powdery	The sensation of small particles like flour
Bell pepper flavor	Perception of bell pepper aroma and taste
Dairy flavor	Aroma and taste associated with cream/milk

chosen. Participants were free to choose the same attribute for the same cheese sample as often as necessary. Finally, when participants swallowed, the "stop" button was pressed. TDS evaluations stopped with the moment of swallowing so that the endpoint of the TDS evaluations corresponds to the time point when cheeses were expectorated (100% mastication) to collect the cheese boli. After each sample, participants neutralized their mouth with sparkling water and a piece of white bread. Samples were presented in a randomized order according to a Latin square scheme. The attribute list was randomized across participants but was kept constant for all samples and for an individual panelist.

2.6. Data analysis

To determine the effect of addition of bell pepper gel pieces to each cheese matrix (Hn or Sa) on oral behavior (consumption time, number of chews, number of swallows, eating rate) and on bolus properties (saliva incorporation, bolus hardness, bolus adhesiveness), one-way analyses of variance (ANOVA) were performed between each of the four heterogeneous cheeses and their corresponding homogeneous cheese sample. Furthermore, three-way repeated measures ANOVA was performed to determine the main and interaction effects of cheese matrix type, fracture stress, and concentration of gel pieces on oral behavior (consumption time, number of chews, number of swallows, eating rate) and bolus properties (particle size, particle number, saliva incorporation, bolus hardness and adhesiveness). Effects were considered statistically significant at $p < 0.05$. When interactions were significant, post-hoc analyses with Bonferroni adjustment were performed as follows: a significant three way interaction was followed by simple two-way interaction analysis, simple main effects analysis and simple pairwise comparisons; when non-significant three way interactions but only significant two way interactions were present, they were followed by simple main effects analysis and simple pairwise comparisons.

TDS curves were constructed by plotting the dominance rate (proportion of subjects who scored each attribute at each point of time) against consumption time. In order to take into account differences in consumption time between subjects, consumption time was standardized on a scale from 0 (starting point) to 100 (swallowing moment). Chance and significance level were calculated as described by Pineau et al. (2009).

To investigate the relationships between oral behavior, bolus properties at the moment of swallowing, and sensory perception a Multiple Factor Analysis (MFA) was performed with three data matrices including only cheeses with bell pepper gel pieces. The data matrices were oral behavior, bolus properties and TDS total dominance duration. TDS total dominance duration refers to the average time that an attribute was selected as dominant sensation by the participants. Individuals graphs and correlations circles were plotted for dimensions one and two, and dimensions one and three.

All data analyses were performed in R (v3.6.3; R Core Team, 2019). One-way ANOVA and three-way repeated measures ANOVA analyses were performed using *rstatix* package (v0.4.0; Kassambara, 2020). TDS curves and sensory trajectories were constructed using *tempR* package (v0.9.9.16; Castura, 2020). MFA analysis and graphs were performed with packages *FactoMineR* (v2.3; Husson, Josse, Le, & Mazet, 2020) and *factoextra* (v1.0.7; Kassambara, 2020)

3. Results

3.1. Oral behavior

Means \pm SE of the parameters characterizing the oral behavior of the cheeses are shown in Table 3A. Results of the statistical analyses (Table 4A) show that upon incorporation of gel pieces into soft/adhesive cheese matrices consumption time, number of chews and number of swallows increased and eating rate decreased significantly. Similarly, incorporation of bell pepper gel pieces into hard/non-adhesive cheese

Table 3

Means ± SE of parameters describing (A) oral processing behavior and (B) bolus properties of cheeses varying in matrix type, bell pepper gel pieces fracture stress and bell pepper gel pieces concentration. Sample codes are explained in Table 1.

	Sa (-)	SaSo ₁₅	SaSo ₃₀	SaHa ₁₅	SaHa ₃₀	Hn (-)	HnSo ₁₅	HnSo ₃₀	HnHa ₁₅	HnHa ₃₀
(A) Oral behavior										
Consumption time (s)	10.9 ± 0.4	13.0 ± 0.5	13.0 ± 0.8	13.1 ± 0.5	13.5 ± 0.7	11.2 ± 0.5	11.9 ± 0.5	12.0 ± 0.5	12.9 ± 0.6	13.4 ± 0.7
Number of chews (-)	13.3 ± 0.8	17.3 ± 1.0	18.8 ± 1.4	19.3 ± 1.0	20.0 ± 1.4	14.1 ± 0.1	16.7 ± 1.0	17.7 ± 1.1	18.9 ± 1.0	19.3 ± 1.3
Number of swallows (-)	2.2 ± 0.2	2.0 ± 0.1	2.0 ± 0.2	1.8 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.9 ± 0.1
Eating rate (g/min)	30.1 ± 1.3	25.7 ± 1.0	26.9 ± 1.9	25.4 ± 1.3	25.0 ± 1.5	30.3 ± 1.5	28.6 ± 1.5	28.9 ± 1.6	27.2 ± 1.6	25.6 ± 1.7
(B) Bolus properties										
Number of particles (-)	-	266 ± 18	478 ± 18	272 ± 19	488 ± 18	-	192 ± 15	320 ± 27	203 ± 16	336 ± 29
d50 (mm)	-	2533 ± 50	2538 ± 41	2477 ± 36	2540 ± 46	-	2878 ± 68	2994 ± 77	2977 ± 91	3139 ± 109
Saliva incorporation (mg of saliva / g of food)	182 ± 26	303 ± 27	263 ± 23	274 ± 27	302 ± 25	202 ± 27	185 ± 25	231 ± 23	245 ± 30	249 ± 23
Bolus hardness (N)	2.9 ± 0.2	3.9 ± 0.2	4.9 ± 0.7	4.9 ± 0.6	9.8 ± 1.0	2.0 ± 0.2	2.9 ± 0.2	2.9 ± 0.3	3.9 ± 0.4	6.9 ± 1.0
Bolus adhesiveness (mJ)	7.4 ± 0.5	4.9 ± 0.5	3.0 ± 0.5	5.2 ± 0.5	3.4 ± 0.5	6.9 ± 0.5	4.6 ± 0.5	3.5 ± 0.5	4.4 ± 0.5	3.0 ± 0.3

Table 4

F and p values of the effect of addition of particles to each homogenous matrix. (A) oral processing behavior and (B) bolus properties.

	Soft/adhesive cheese matrix		Hard/non-adhesive cheese matrix	
	F	p	F	p
(A) Oral behavior				
Consumption time (s)	5.45	<0.001	5.91	<0.001
Number of chews (-)	13.59	<0.001	11.62	<0.001
Number of swallows (-)	3.02	0.02	0.28	0.893
Eating rate (g/min)	7.14	<0.001	3.84	0.006
(B) Bolus properties				
Saliva incorporation (mg of saliva / g of food)	13.50	<0.001	5.41	<0.001
Bolus hardness (N)	20.73	<0.001	21.15	<0.001
Bolus adhesiveness (mJ)	34.14	<0.001	44.42	<0.001

matrices significantly increased consumption time and number of chews and decreased eating rate. In average, the addition of bell pepper gel pieces to soft/adhesive cheeses increased consumption time by 20.6% (from 10.9 to 13.2 s) and number of chews by 41.7% (from 13.3 to 18.9). Addition of bell pepper gel pieces to hard/non-adhesive cheeses increased consumption time by 12.0% (from 11.2 to 12.6 s) and number of chews by 28.7% (from 14.1 to 18.2). Addition of bell pepper gel pieces decreased average eating rate by 14.5% (4.4 g/min) for soft/adhesive cheeses and by 8.9% (2.7 g/min) for hard/non-adhesive cheeses.

Furthermore, the results showed that, among the heterogeneous

Table 5

F and p values of main effects and interactions of three-way repeated measures ANOVA analysis for (A) oral processing behavior and (B) bolus properties of heterogeneous cheeses. Three-way repeated measures ANOVA was performed only on heterogeneous cheeses.

	Cheese matrix		Gel fracture stress		Gel concentration		Matrix: Gel fracture stress		Matrix: Gel concentration		Gel fracture stress: Gel concentration		Matrix: Gel fracture stress: Gel concentration	
	F	p	F	p	F	p	F	p	F	p	F	p	F	p
(A) Oral behavior														
Consumption time (s)	5.98	0.020	6.04	0.020	0.73	0.400	1.91	0.176	0.01	0.932	0.52	0.475	0.01	0.922
Number of chews (-)	1.72	0.199	21.26	<0.001	2.84	0.102	0.14	0.707	0.20	0.660	0.49	0.487	0.025	0.876
Number of swallows (-)	0.24	0.625	1.98	0.169	0.1	0.757	4.86	0.035	0.33	0.572	0.05	0.823	0.00	1.000
Eating rate (g/min)	7.38	0.011	4.88	0.034	0.04	0.840	0.99	0.328	0.50	0.484	1.48	0.233	0.03	0.872
(B) Bolus properties														
Number of particles (-)	21.27	<0.001	1.18	0.287	485.30	<0.001	0.9	0.351	17.2	<0.001	0.47	0.499	0.08	0.776
d50 (mm)	22.68	<0.001	2.70	0.111	6.77	0.015	5.7	0.024	2.13	0.155	1.36	0.254	0.001	0.991
Saliva incorporation (mg of saliva / g of food)	15.97	<0.001	5.05	0.032	0.38	0.542	2.81	0.104	3.74	0.063	0.36	0.552	15.60	<0.001
Bolus hardness (N)	18.02	<0.001	40.11	<0.001	29.88	<0.001	1.92	0.180	2.88	0.104	12.73	0.002	0.46	0.506
Bolus adhesiveness (mJ)	0.74	0.401	0.02	0.881	87.29	<0.001	4.67	0.042	3.31	0.082	0.03	0.866	0.27	0.611

cheeses, those with soft/adhesive matrix took 4.5% longer to be consumed (13.2 s) and led to 7% lower eating rate (25.8 g/min) than cheeses with hard/non-adhesive matrix (12.6 s and 27.6 g/min, respectively). Furthermore, the consumption time of cheeses that had bell pepper gel pieces with high fracture stress was 5.3% longer (13.2 s) than cheeses with gel pieces with low fracture stress (12.5 s) and led to 6.2% lower eating rate (25.9 vs. 27.5 g/min, respectively). Cheeses with high fracture stress gel pieces had significantly higher number of chews (19.4) than cheeses with gel pieces with low fracture stress (17.4). Fracture stress of bell pepper gel pieces had also a significant effect on number of swallows but only when interacting with cheeses with soft/adhesive matrix. The concentration of gel pieces did not have a significant effect on any oral processing behavior parameters (Table 5A).

3.2. Bolus properties at moment of swallowing

Means ± SE of the parameters characterizing bolus properties of the expectorated cheeses are shown in Table 3B. The results of the statistical analyses (Table 4B) show that upon incorporation of gel pieces into soft/adhesive cheese matrices saliva incorporation significantly increased from 182 to 285 mg/g, and bolus hardness increased from 2.9 to 5.9 N, whereas bolus adhesiveness decreased from 7.4 to 4.1 mJ. Same trends were found after incorporation of bell pepper gel pieces into hard/non-adhesive cheese matrices where saliva incorporation significantly increased from 202 to 227.5 mg/g, bolus hardness increased from 2.0 to 4.15 N, and bolus adhesiveness decreased from 6.9 to 2.9 mJ.

Additionally, results of the statistical analyses of the effects of matrix,

bell pepper gel pieces fracture stress and concentration on bolus properties of heterogeneous cheeses, show that for number of particles there was a significant interaction between cheese matrix and bell pepper gel pieces concentration (Table 5B). Cheeses with soft/adhesive matrix and high concentration of gel pieces (Sa₃₀) produced boli with significantly more particles than cheeses with hard/non-adhesive matrix and low concentration of bell pepper gel pieces (Hn₁₅). Concentration of gel pieces had a significant effect on d_{50} with cheeses with high concentration of gel pieces having larger d_{50} . Besides, there was a significant interaction between matrix and bell pepper fracture stress that had an influence on the median size of the bolus fragments d_{50} . Cheeses with hard/non-adhesive matrix and gel pieces of high fracture stress (HnHa₁₅) had larger d_{50} compared to cheeses with similar matrix but with gel pieces of low fracture stress (HnSo₁₅).

For the mass ratio of saliva incorporated in the bolus (h_w), a significant three-way interaction was found. After post-hoc analyses, high concentration of soft gel pieces caused a higher saliva incorporation in the bolus of cheeses with hard/non-adhesive matrix (HnSo₃₀) than low concentration of the same type of gel pieces (HnSo₁₅). On the other hand, there was significantly higher saliva incorporation in the bolus of cheeses with a hard/non-adhesive matrix, high fracture stress, and bell pepper gel pieces present in low concentration (HnHa₁₅) than in similar cheeses but with low fracture stress bell pepper gel pieces (HnSo₁₅).

Cheeses with hard/non-adhesive matrices produced bolus with significantly lower hardness than cheeses with soft/adhesive matrices. A significant interaction between gel pieces fracture stress and gel pieces concentration showed that when both parameters increased, bolus hardness significantly increased. Cheeses with high concentration of particles (30%) had significantly lower bolus adhesiveness than cheeses with low concentration of particles (15%). A significant interaction between cheese matrix and gel pieces fracture stress was observed for bolus adhesiveness, however after post-hoc analyses the effect disappeared.

3.3. Temporal dominance of sensations (TDS)

Normalized TDS curves of all cheeses are shown in Fig. 1. The dominant sensation of the homogeneous, soft/adhesive cheese was sticky for the first half of consumption time. Simultaneously present dominant sensations after 20% of consumption time were creamy and smooth. Dairy flavor and melting sensation became dominant in the second half of consumption time and remained dominant sensations until swallowing. The homogeneous, hard/non-adhesive cheese was perceived as firm during the first 25% of consumption time. Then the dominant sensation became dairy flavor and around 50% of consumption time melting and smooth sensations became dominant together with dairy flavor. Close to swallowing sticky became dominant but at low dominance rate.

For heterogeneous cheeses, the number of attributes reaching significance decreased with increasing fracture stress and concentration of gel pieces. Processed cream cheeses with soft/adhesive matrices showed higher dominance rates and longer dominance durations for creaminess, dairy flavor, smoothness and melting compared with processed cream cheeses with hard/non-adhesive matrices. Increasing fracture stress of bell pepper gel pieces decreased dominance rate and duration of creaminess and bell pepper flavor while dominance rate and duration of graininess increased. Incorporation of gel pieces at high concentration (30% w/w) reduced dominance rate and duration of creaminess, melting and dairy flavor while dominance rate and duration of graininess and bell pepper flavor increased and remained dominant during the entire consumption time.

3.4. Relationships between oral behavior, bolus properties and dynamic sensory perception

explain 86.2% of the variance in the data. Fig. 2A shows the position of the eight cream cheeses with gel pieces relative to each other in the first two dimensions. Fig. 2B shows the correlations between the variables. The first dimension is mainly explained by differences in oral behavior separating cheeses with a high concentration of high fracture stress pieces from cheeses with a low concentration of low fracture stress bell pepper pieces. In this dimension, it can be observed that that number of chews and total consumption time were positively correlated, and both were negatively correlated with eating rate. Consumption time and number of chews were correlated with bolus properties such as saliva content, number of bolus particles and bolus hardness as well as with sensory perception of firmness, chewiness and graininess. Cheeses that were masticated for longer time and with more chews incorporated more saliva and were broken down into more fragments which corresponds to cheeses that contain gel pieces with high fracture stress at high concentration. The second dimension is for the most part explained by the sensory attributes dividing cheeses with soft/adhesive matrix from cheeses with hard/non-adhesive matrix. Creaminess, smoothness, stickiness, melting and dairy flavor were positively correlated with each other and with bolus adhesiveness. These variables described cheeses with soft/adhesive matrices and gel pieces at low concentration (₁₅) with soft and hard gel pieces. Besides, bolus particles size was positively correlated with sensory attributes powdery and bell pepper flavor and negatively correlated with creaminess, smoothness, stickiness, melting and dairy flavor. The later attributes were also negatively correlated with grainy and chewy attributes in the first dimension.

The third dimension (Fig. 2C and D) shows a positive correlation between total number of bolus particles, bell pepper flavor and number of swallows; variables that describe a cheese with soft/adhesive matrix, soft gel particles at high concentration (SaSo₃₀). Similar to dimension two, dimension three shows that bolus adhesiveness, and dairy flavor were positively correlated. Lastly, adding the third dimension shows that there was a positive correlation between eating rate and melting, creamy and smoothness in the first dimension that describes cheeses with embedded soft gel pieces.

4. Discussion

4.1. Effect of addition of bell pepper gel pieces into homogeneous processed cream cheeses on oral behavior, bolus properties and sensory perception

We hypothesized that the extent to which oral behavior is affected by the addition of particles to foods depends on the magnitude of the difference in mechanical properties between particles and matrix. Our results showed that, independently of the gel characteristics, the mere addition of particles into cream cheeses, showed a similar influence on oral behavior than the one previously observed in another study of yogurts where addition of peach gel particles increased number of chews and consumption time and consequently reduced eating rate (Aguayo-Mendoza et al., 2020). However, the impact of addition of bell pepper gel pieces to processed cream cheeses on oral behavior was smaller than the impact previously reported for addition of peach gel pieces to yogurt, since mechanical contrast between food matrix and embedded particles was smaller. Thus, the mere addition of solid particles is a favorable strategy to steer oral behavior not only when incorporated into liquid foods but also when added to semi-solid foods. This strategy can be especially relevant since subtle food texture modifications are more easily sustained, implemented and accepted by consumers and can be used to potentially moderate food intake (Mosca et al., 2019). Nevertheless, the magnitude by which oral processing behavior was modified depended on the texture of the cheese matrix. In soft/adhesive cheese matrices the effect of addition of particles on oral processing behavior was almost twice as large than in hard/non-adhesive cheese matrices. When gel pieces were incorporated into soft/adhesive cheese matrices, eating rate decreased from 30.1 g/min for the homogeneous

Fig. 2 displays the first three dimensions of the MFA which together

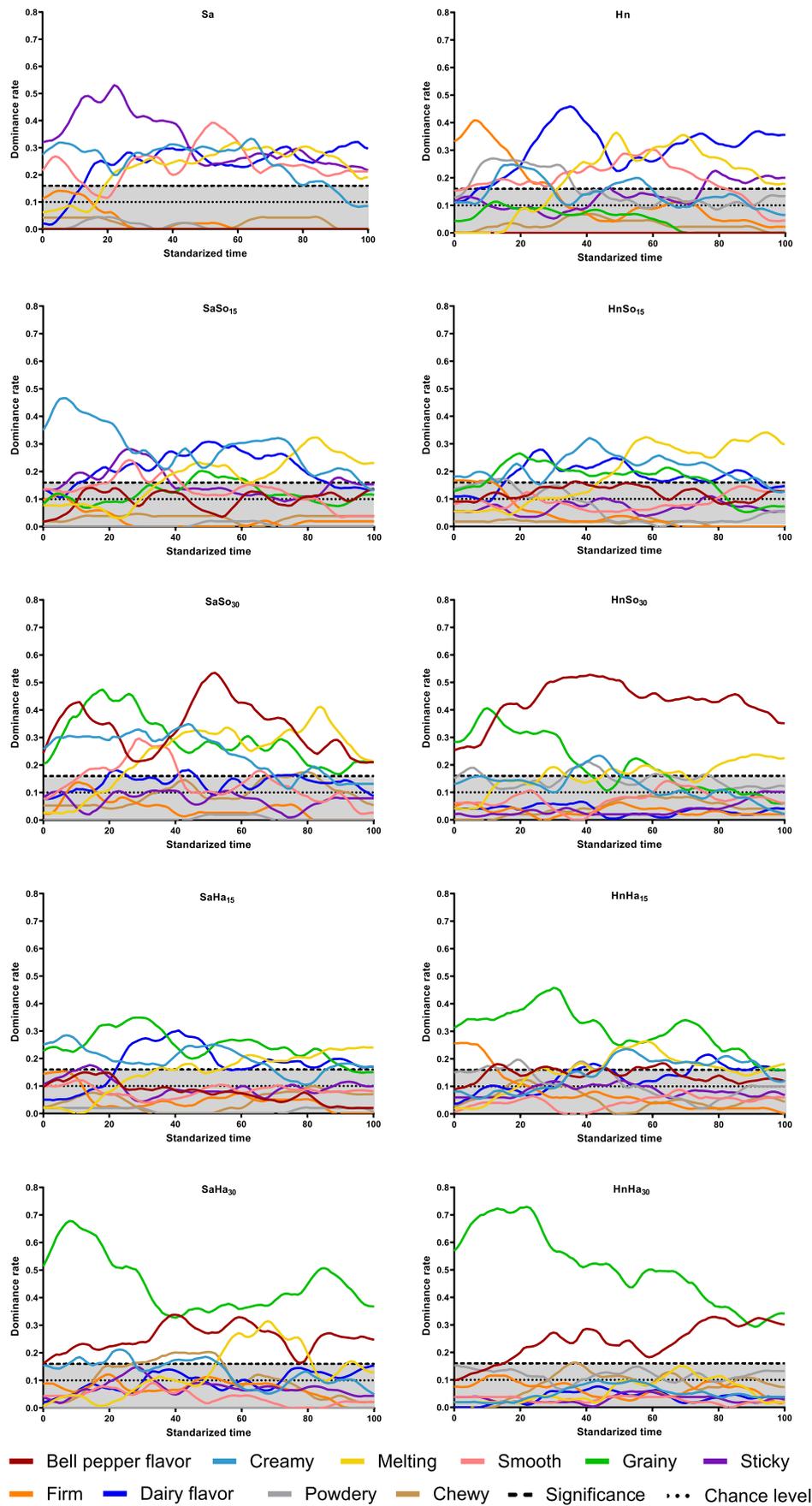


Fig. 1. Temporal Dominance of Sensations (TDS) curves (n = 34, duplicate) of processed cheeses without and with bell pepper gel pieces. Sample codes are explained in Table 1.

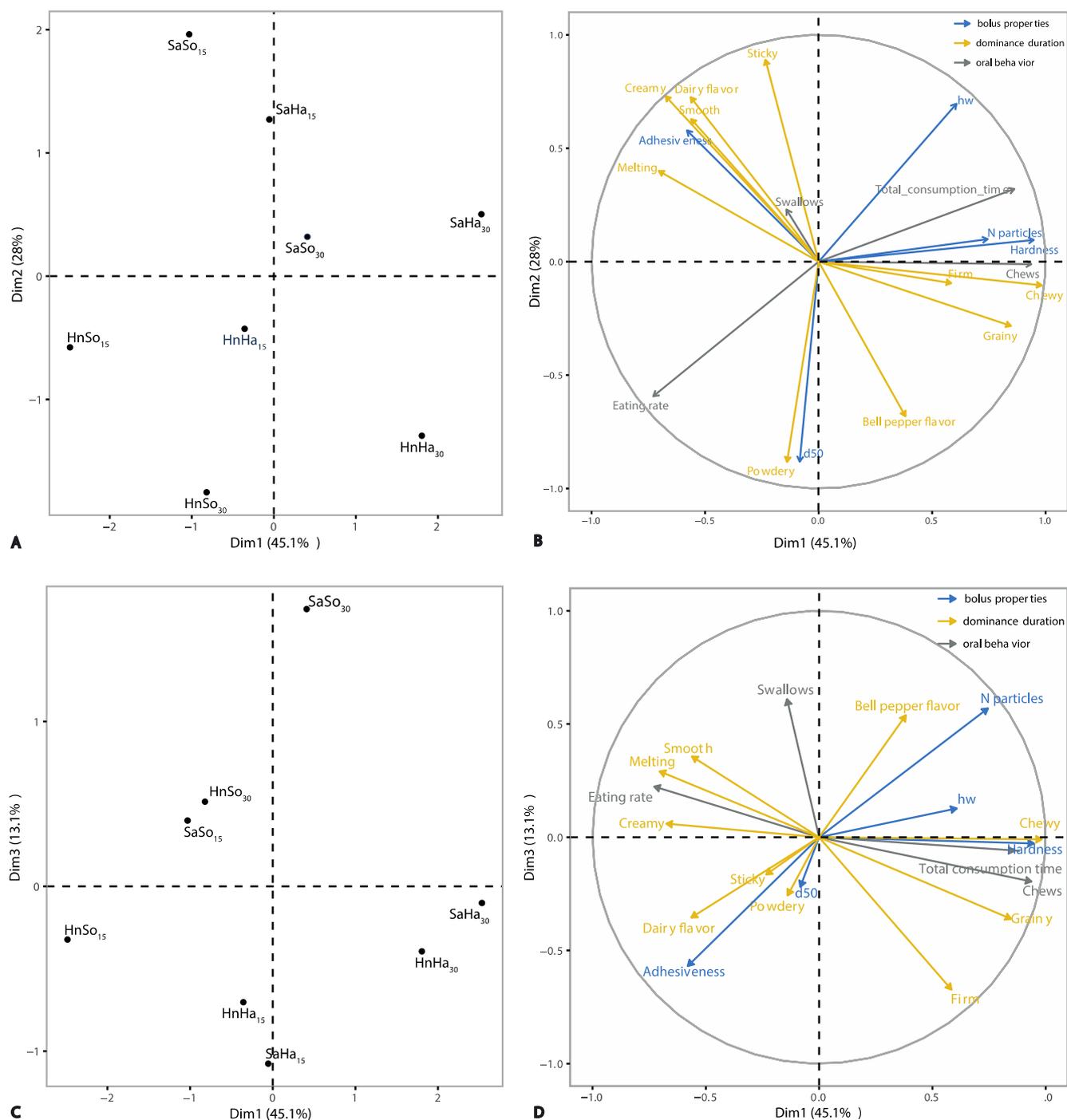


Fig. 2. A) MFA sample space depicting dimension one and two. B) Correlation circle displaying relationships between variables describing oral behavior (gray), bolus properties (blue) and TDS dominance durations (yellow) of dimensions one and two. C) MFA sample space depicting dimensions one and three. D) Correlation circle displaying relationships between the variables describing oral behavior (gray), bolus properties (blue), and TDS dominance durations (yellow) of dimensions one and three. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cheese to an average of 25.7 g/min (-14.5%) for the heterogeneous soft/adhesive cheeses, while for homogeneous hard/non-adhesive cheese matrices eating rate decreased from 30.3 g/min to 27.6 g/min (- 8.9%). Therefore, when designing heterogeneous food structures with the desire to influence oral behavior, the characteristics of the matrix and the mechanical contrast between particles and matrix need to be considered.

The properties of the bolus at the swallowing point were also affected by the incorporation of gel pieces. Upon addition of gel pieces to the cheeses, the amount of saliva incorporated in the bolus and bolus

hardness increased whereas bolus adhesiveness decreased. Surprisingly, hardness and adhesiveness showed very similar increments in both cheese matrices. Whereas the increment in saliva was greater when the cheese matrix was soft/adhesive than hard/non-adhesive (increment of 56.8 and 12.62% respectively); this discrepancy in the increment of saliva between the matrices could be connected to the relative changes in consumption time and number of chews.

With regards to dynamic sensory perception, as expected the addition of particles reduced the dominance rate and duration of attributes that mainly describe the cheese matrices (creaminess, smoothness,

melting and dairy flavor) while dominance rate and duration of attributes describing the bell pepper gel pieces (graininess and bell pepper flavor) increased.

4.2. Influence of cheese matrix and gel pieces characteristics on oral behavior of heterogeneous cheeses

Cheeses with soft/adhesive matrix were consumed for 4.5% longer time than cheeses with hard/non-adhesive matrix. It would be expected that cheeses with hard matrices would be processed orally for longer time. However, the slight elongation on consumption time of the soft/adhesive cheese matrices might be attributed to its higher adhesiveness rather than its lower hardness most likely because of additional mouth clearance. The number of chews was not affected by cheese matrix type but by fracture stress of embedded bell pepper gel pieces which also prolonged consumption time. We conclude that not only food hardness but also other texture characteristics such as adhesiveness contribute to consumption time (Wagoner, Luck, & Foegeding, 2016).

4.3. Influence of cheese matrix and gel pieces characteristics on bolus properties of heterogeneous cheeses

Bolus properties at the swallowing point were influenced by the properties of the cheese matrix and the bell pepper gel piece characteristics. Number of bolus particles was higher when concentration of bell pepper gels pieces was high (30% w/w) in soft/adhesive cheese matrices. We speculate that oral detection of gel piece fragments might be more evident when fragments are embedded in a soft matrix than when they are embedded in a hard matrix. Gel fragments in soft/adhesive matrices may be selectively moved towards the molars to be comminuted, which might also explain why bolus particles from soft/adhesive matrices were in smaller (2522 μm) than particles from hard/non-adhesive matrices (2997 μm). Another interesting fact is that the bolus particle size of the gels in these heterogeneous cheeses is larger than the size previously reported for homogeneous foods. A previous study suggested that homogeneous foods such as peanuts, mushrooms, carrots or ham should reach a particle size smaller than 2000 μm before being swallowed unless particles are soft enough to avoid injury of the upper digestive mucosa (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007). In our study, gel pieces were embedded in a cheese matrix which upon chewing could serve as coating layer decreasing the friction between the bolus particles and the oral mucosa facilitating swallowing.

Saliva incorporation in the bolus increased in cheeses with hard/non-adhesive matrices and low concentration of particles (15% w/w) when fracture stress of the bell pepper gel pieces was increased from 100 to 300 kPa. This increase in saliva incorporation might be caused by higher mechanical stimulation subsequent to the increment in the hardness of the gel pieces, which in turn increases the salivary flow (Anderson & Hector, 1987).

Bolus hardness and adhesiveness were predominantly influenced by the characteristics of the gel pieces. During compression, the presence of particles influenced the force necessary to deform the bolus so that an increase in gel fracture stress or gel pieces concentration increased bolus hardness. On the contrary, increasing the concentration of gel pieces decreased bolus adhesiveness by limiting the contact surface of the cheese structure.

4.4. Influence of cheese matrix and gel pieces characteristics on dynamic sensory perception of heterogeneous cheeses

The dynamic sensory perception of heterogeneous cheeses was influenced by the cheese matrix texture and bell pepper gel pieces properties. Cheese matrices with hard/non-adhesive texture displayed lower dominance durations and dominance rates for creaminess, smoothness and melting sensations than cheese matrices with soft/

adhesive texture. The differences in sensory properties between the cheeses may be explained by the presence of k-carrageenan in the hard/non-adhesive cheese matrices. Previous studies have shown that the addition of k-carrageenan increased cheese hardness producing a negative effect on meltability (Ahmad, Butt, Pasha, & Sameen, 2016; Błaszak, Gozdecka, & Shyichuk, 2018; Černíková et al., 2010). Melting perception might therefore have been reduced contributing to a decline in smoothness and creaminess (Çakir et al., 2012; Kokini, 1987).

With increasing concentration of gel pieces, dominance rate and duration of bell pepper flavor increased. Increasing the concentration of particles expands the contact area between the gel pieces and the tongue which might have contributed to a higher dominance of bell pepper flavor. Higher concentrations of gel pieces led to a lower dominance rate and duration of creaminess, melting and dairy flavor while graininess increased and remained significantly dominant during the entire consumption time. Graininess perception has been related to the detectability of particles in the mouth, so adding particles or increasing their concentration is expected to rise graininess perception. When in addition to the concentration of gel pieces, these were of low fracture stress, then bell pepper flavor showed higher dominance rate. Taste and aroma perception are influenced by fracture stress of foods. Increasing fracture stress leads to decreasing taste and aroma perception (Mosca, van de Velde, Bult, van Boekel, & Stieger, 2015; Tournier, Sulmont-Rossé, & Guichard, 2007).

An unexpected result was that several attributes were dominant for long periods resulting in little temporal dynamics among the attributes for several cheeses. Only firmness and melting showed some dynamics over the consumption time. Firmness was only perceived at the beginning of consumption time, but this sensation was only dominant in the homogeneous hard/non-adhesive cheese. Whereas melting was a sensation always perceived after some degree of oral manipulation, which may be needed to bring the food to mouth temperature before the meltiness is perceived. On the other hand, attributes that show the lowest dynamics were graininess and bell pepper flavor, both attributes are dependent on the presence of bell pepper gel pieces. Upon mastication, bell pepper pieces become more numerous but with smaller size, so the perception of graininess and bell pepper flavor remains. Thus, there seem to be attributes that need certain transformation of the food structure during oral processing in order to be perceived whereas other attributes may be more stable over time with changes just in their intensity.

4.5. Relationships between oral processing, bolus properties and sensory perception

Oral behavior (consumption time and number of chews) was positively correlated with several bolus properties (saliva incorporation, number of bolus particles and bolus hardness) and with perception of several sensory attributes (firmness, graininess, chewiness). These relationships were found in heterogeneous cheeses with bell pepper gel pieces of high fracture stress and high concentration independent of the cheese matrix. The addition of bell pepper gel pieces with high fracture stress prolonged consumption time compared to the softer counterpart. This is in agreement with several other studies that demonstrated that mastication time increases when hardness or stiffness of foods increase (Agrawal et al., 1998; Aguayo-Mendoza et al., 2019; Doyennette et al., 2019; Engelen et al., 2005; Foster et al., 2006; Koç et al., 2014; Kohyama et al., 2016; Mioche et al., 2003; Peyron et al., 2002). Furthermore, increments in consumption time caused by presence of bell pepper gel pieces with high fracture stress on both cheese matrices gave rise to more saliva incorporation into the bolus. It is known that increments in mastication time will in turn increase salivation, so the increase in saliva incorporation in the bolus might be caused by the prolonged consumption time. Moreover, the increased number of chews increment the number of bolus particles which clearly relates with attributes such as graininess. Graininess perception has been linked to the presence of food

particles and their oral selection for further bolus degradation in order to reduce particle size (Fizman & Tarrega, 2018). Firmness and chewiness of foods have been correlated with expected satiation (Forde, Leong, Chia-Ming, & McCrickerd, 2017). Therefore, we suggest that incorporating particles to foods that increase perceived firmness and chewiness without increasing energy content could aid in regulating energy intake. This approach should be considered carefully though, since the presence of chewiness and/or graininess in foods where these sensations are not expected, can reduce acceptability, however when these perceptions are congruent with the product palatability can be maintained (Santagiuliana et al., 2019).

Consumption time and number of chews were negatively correlated with faster eating rate. Faster eating rate was positively correlated with smoothness, creaminess and meltiness sensations. This was specially observed in heterogeneous cheeses that contained soft particles independently of the matrix characteristics (Fig. 2D). Smoothness, creaminess and meltiness are sensations that are commonly found after some degree of oral processing and are related to the absence of large particles in the bolus (de Wijk, Janssen, & Prinz, 2011; Fizman & Tarrega, 2018), thus it is probable that faster eating rates are connected to attributes that resemble a more bolus like structure.

Overall, the magnitude of the effect by which oral behavior is affected, may depend on the food combination used and on whether a texture contrast is perceived or not. Therefore, further studies should make a systematic variation on the combination of food items across different food categories to observe how the different combinations behave and to define how big should be the texture contrast in order to impact oral behavior.

5. Conclusions

The present research studied the effect of heterogeneous food components, processed cheese matrix and embedded bell pepper gel pieces, on oral processing, bolus properties and dynamic sensory perception. Both matrix and gel pieces characteristics effected consumption time, eating rate, number of chews, bolus particle size distribution, saliva incorporation, bolus hardness and adhesiveness, as well as perception of sensory attributes. The magnitude of the effect depended on the specific combination of the mechanical properties of both food items (i.e. matrix and gel pieces). Therefore, we conclude that when two homogeneous foods are combined, the physicochemical properties of the foods may elicit a sensory contrast that lead to a different oral behavior, bolus breakdown and sensory perception that would not be anticipated on the basis of the separate homogeneous components. We suggest that the modification of food properties by manipulation of one of the food components can be a convenient strategy to steer oral behavior which could potentially influence on food intake.

CRedit authorship contribution statement

Monica G. Aguayo-Mendoza: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing, Supervision. **Georgia Chatonidi:** Methodology, Investigation. **Betina Piqueras-Fizman:** Writing - review & editing. **Markus Stieger:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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