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The eating rate of bread predicted from its sensory texture and physical properties†

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Eating rate (ER) can moderate energy intake and ER can be modified by the texture and physical properties of food. However, the magnitude of the effects is not well known. The aim of this study was to investigate how bread texture and physical properties determine ER. In a randomised crossover study, 36 healthy participants (age: 25 ± 6 years, BMI: 22 ± 2 kg m^{-2}) consumed nine different bread types. Video coding was used to characterise oral processing behaviour. Sensory texture was evaluated on visual analogue scales. Physical properties were measured using texture profile analysis, puncture tests, geometrical and water-related measures. Two models were developed using response surface methodology (RSM) that predict the ER based on sensory and physical properties. The results showed from slow to fast ER: bread slices < hard buns < soft buns. The slowest bread type (wholemeal bread slice) was consumed 40% slower than the fastest bread type (soft white bun) ($P < 0.001$), explained by smaller bite sizes and more chews. For the sensory texture, ER was positively correlated with crumb adhesiveness and negatively correlated with crumb dryness. For the physical properties, ER was positively correlated with height and volume, and negatively with crumb cohesiveness and crust hardness. The models based on physical properties (R^2 = 0.91) and sensory texture (R^2 = 0.89) were both able to estimate ER, but the model based on physical properties performed slightly better. The insights from the relationships from the sensory and physical measures can both be used to modify the texture of breads, to effectively decrease ER and eventually help to prevent overconsumption.

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1. Introduction

Global overweight and obesity rates are high and still increasing.[1] It has consistently been shown that energy intake is decreased by a slower eating speed.[2–4] The speed of eating is often called eating rate (ER) and is defined as the amount of grams consumed per unit of time (g min^{-1}). A foods' texture is the major determinant of ER[5–7] next to minor effects of flavour intensity,[8] eating environment and individual characteristics such as preference, familiarity, oral physiology, age, and gender.[9,10] Textures that are well known to decrease ER are elasticity and hardness,[7,11–17] whereas effects of some other food texture properties like lubrication, cohesiveness and adhesiveness are not systemically researched.[18]

Bread is a staple food and is consumed in almost all countries,[19] providing a substantial contributor to the total energy intake of the diet.[20,21] For instance, in the Netherlands 3.5 of bread slices are consumed on average per day (126 grams per day).[20] Bread products are around for a long time and have evolved to take many forms, leading them to have different and distinctive characteristics.[19] By changing their formulation or processing, for example by changing the ingredients, mixing, shaping, proofing, baking, or cooling, the texture of bread can be modified and consequently the oral processing behaviour.[22–25] The effect of texture on oral processing is dominant for the bread crust over the effect of the bread crumb.[25,26] For example, a baguette with a thick and dry crust has a larger chewing duration than a steamed bread with a moist and soft skin.[27] Crust hardness and the dryness of bread are seen as two of the most important factors determining the chewing duration of bread.[25] Nevertheless, it is not known how other texture properties modify the ER of bread and which properties have the largest effect.

To get an understanding of the quantitative relationships between food texture and ER, mathematical modelling is a promising technique as it can give valuable insights in the relevance of measures. Mathematical modelling is amongst

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others used in food flavour analysis, sensory profiling, and hedonic testing,[28] but its use in eating behaviour analysis is very limited. To model the effect of texture on eating behaviour, sensory texture evaluations or physical measurements of bread properties could be used.[29] Instrumental or physical measurements are considered to be less costly and more precise, however the translation to oral processing characteristics is not always clear.[30] On the other hand, sensory evaluation is subjective with large individual differences and are generally expensive and time consuming.[29,31] Overall, it is unclear how accurate sensory texture and physical properties of bread can predict the ER of bread and which method is most reliable to predict ER. If the models predicting ER are accurate, they could be useful for the design of food products for special needs of low or high ER.

The aim of the research was to assess how various bread textures and physical properties affect ER and to investigate how well they can predict ER. Insights in relevant texture and physical properties that determine ER may help to develop breads that promote or limit intake.

2. Materials and methods

2.1 Experimental design

In this study instrumental texture (*i.e.* TPA), geometrical properties, water content and absorption, sensory texture, oral processing behaviour and saliva incorporation of commercially available breads were assessed. This was used to develop models that predict the ER of the breads. The study was approved by the Social Sciences Ethical Committee of Wageningen University and was registered at Clinical Trial registry: NCT05185765.

2.2 Bread samples

Participants consumed and evaluated in total sixteen different bread types of which nine are included in this analysis. Seven different breads slices were excluded from analysis since they had minimal differences in textural properties (all wholemeal bread slices). The nine included bread types were commercially available (all Albert Heijn private label, except for ciabatta [Jan Linders private label]). The bread slices and soft buns were frozen at −20 °C and thawed 2–5 hours before usage at room temperature while wrapped in plastic foil to avoid staling. The hard buns, ciabatta and croissant were bought on the morning of the measurements. All the bread types were cut to obtain half a unit of bread (*e.g.* half a bread slice or half a bread bun) for oral processing and sensory measurements. Pilot tests indicated that this amount of bread was enough to allow for several bites but prevented the participants for becoming full.

For studying the saliva uptake, breads were cut in bite size pieces. The bite size pieces of the bread slices were made by cutting the lower half of the bread slices in four pieces and the bite size pieces of soft buns by cutting them in eight pieces. The bite size pieces of the hard buns, ciabatta and croissant were obtained by cutting one slice of 1 cm thickness in half. The pictures and weights of the samples can be found in Table 1.

2.3 Participants

Participants were recruited from Wageningen and surroundings using an e-mailing list, social media and flyers. Healthy (self-reported), normal weight (18.5–30 kg m^{-2}) men and women with Dutch nationality and between 18–55 years old were included. Additionally, they had to consume bread at least once a week. Exclusion criteria were: dislike bread products, smoking, following a vegan diet, allergies or intolerance to any ingredient of the breads, suffering from diabetes, having taste or smell disorders, difficulties with swallowing, chewing and/or eating in general, use of medication that may influence study outcomes, pregnant or lactating women, men having facial hair such as a beard as facial movements cannot be analysed, braces (not including a dental wire) or oral piercing, consuming on average more than 21 glasses of alcohol per week, and not willing to stop using drugs during the study period (from inclusion till last test session). Participants were informed that the study aimed to investigate the effect of structural properties on the sensorial characteristics of bread. Participants received a monetary incentive for their participation.

After screening and giving their written consent, 36 participants (12 males; 33%) were included and completed the whole study. The participants were 25 ± 6 years old and had an average BMI of 22 ± 2 kg m^{-2} (mean ± SD).

2.4 Procedure

Participants came once a week for a test session during lunch time to the Wageningen University. Participants could choose between three time slots (starting at 11 AM, 12 PM or 13 PM) applicable to all four test sessions. During the whole study period, participants were instructed to not use drugs and to report medication use and illness. To standardize appetite, participants were instructed to refrain from eating and drinking—except for water—after 10 PM on the day before the test session. In the mornings of the test sessions, participants were instructed to refrain from intensive exercise and to have the same breakfast and morning snack around the same time (not provided). Additionally, participants were not allowed to eat or drink two hours prior the test session, except for water. The participants were seated visually separated from each other. They were provided with a paper instruction form describing the procedure and explaining the sensory attributes (Table 2), two 200 mL cups of water, and a laptop with an integrated webcam and online questionnaire (Qualtrics XM, version September 2021, London, England).

At the start of each session, an oral explanation of the procedure of the test session was given. Thereafter, the evaluation of oral processing behaviour and sensory properties were measured in two steps. In the first part, participants consumed half a unit of four different bread types in randomized order. Participants were instructed to consume the whole sample and

Table 1 Pictures and sample weights of the nine bread types. Values are means ± SD

Bread types	Picture of half a unit	Weight of half a unit (g)	Picture of bite size piece	Weight of bite size piece (g)
Wholemeal bread slice		18.5 ± 1.1		5.9 ± 0.3
Brown bread slice		18.1 ± 1.1		5.5 ± 0.2
White bread slice		17.1 ± 1.1		4.9 ± 0.2
Hard brown bun		38.1 ± 1.9		6.0 ± 0.7
Hard white bun		38.7 ± 2.3		6.4 ± 0.6
Soft brown bun		25.7 ± 1.4		7.2 ± 1.1
Soft white bun		25.9 ± 1.6		6.5 ± 0.6
Ciabatta		41.0 ± 3.8		7.4 ± 1.0
Croissant		24.8 ± 1.8		5.6 ± 0.9

to eat as they would normally do, without taking breaks or sips of water. The oral processing behaviour during consumption was determined using video recordings. After each sample, participants rated liking, and the sensory properties (explained in 2.6) of the bread. In between samples, participants had to wait for one minute during which they were asked to take a sip

Table 2 Descriptions of the sensory texture properties (translated from Dutch to English)

Texture	Description
Crumb	
Hardness	How much force is required to deform the bread?
Dryness	How dry feels the sample in your mouth?
Chewiness	How much do you need to masticate before you can swallow the bread?
Adhesiveness	How much force is required to remove the bread that adheres to your palate/lips/teeth?
Denseness	How compact feels the bread after chewing it with your molars? Is the bread very firm or feels the bread very airy?
Crust	
Hardness	How much force is required to deform the bread?
Crispiness	How easily does the crust break if you bite?
Crumbliness	To what degree crumbles the bread upon biting and chewing?

of water to clean their mouth and to neutralize their palate. In the second part, participants were provided with four times two bite sized pieces of bread. These were the same bread types as those consumed in the first part. Participants were instructed to chew on one sample at a time until they feel the urge to swallow. At this point the participants expectorated the sample into an aluminium cup. The boli of two pieces of each bread were separately collected to obtain duplicate measurements. The participants were instructed to rinse their mouth after each chew-spit cycle.

2.5 Oral processing behaviour

During the whole test session participants were video recorded using the integrated webcam of the laptops and Open Broadcaster Software (OBS studio, version 28.1.2). Participants were instructed to look straight into the webcam during the consumption of the samples and not to make excessive head movements. Oral processing behaviour was manually annotated by trained video coders using a coding scheme developed previously[32] using the software ELAN version 6.2 (Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen, The Netherlands). Beforehand defined indicators were number of bites, number of chews, duration per bite, and total sample consumption time. One session of every participant (four samples) was coded by three experimenters to determine coding consistency (25% of the videos). The intraclass correlation coefficient (ICC) between the three coders was between 0.986 and 1.000 across all oral processing behaviours. This indicated excellent consistency (ICC >0.90).[33] The experimenters divided the rest of the videos and coded them independently. The ER (g min^{-1}) was calculated by dividing the total sample weight by the total consumption duration of the sample. The average bite weight (g) was calculated by dividing the weight of the sample by the total number of bites of the sample; average bite volume (cm^3) by dividing the volume of the sample (explained in 2.7) by the total number of bites of the sample; the number of chews per gram (chews per g) by dividing the number of chews by the weight of the samples; the number of chews per bite (–) by dividing the number of chews by the number of bites; the oro-sensory exposure (OSE) time (s g^{-1}) by dividing the summation of the bite durations by the weight of the samples; and the chewing frequency (chews per s) by the number of chews by the OSE time.

Saliva incorporation of the bite size pieces at time of swallowing was measured by dry matter content analysis. Participants expectorated the boli on aluminium dishes. These aluminium dishes were weighed pre and post drying for 20 h at 110 °C. Non-masticated bite size reference pieces were weighed and dried to calibrate for the initial water content of the bread types. The saliva incorporation was calculated using $SI = (m_b - m_0)/m_0$ where SI is the saliva incorporation (g saliva/g bread), m_0 is the weight of the bite sized bread sample (g), m_b the weight of the bolus before drying (g). In this case m_0 was calculated as $m_0 = m_{bd}/(1 - x_w)$, where m_{bd} is the weight of the bolus after drying and x_w the water fraction of the bread before mastication, to correct for the unintentionally swallowed bread and the bread which might have stayed in the mouth after expectoration. As saliva consists of approximately 99% water,[34] the solid content of the saliva was neglected.

2.6 Sensory texture and liking ratings

Participants rated the liking and texture of each bread after consumption on a 100 mm anchored line scale ranging from 'not at all' (0) to 'extremely' (100). Descriptions of the included texture properties were provided to the participants (Table 2).

2.7 Measurements of physical properties

The measurements of the physical properties included texture profile analyses (TPA), puncture tests, geometrical measures, density measures, moisture content and water absorption capacity.

TPA with the TA.XT Plus Texture Analyser (Stable Micro Systems Ltd., Surrey, UK) was used to determine the hardness (g), springiness (–), cohesiveness (–), chewiness (g), resilience (–), and adhesiveness (g s) of the bread crumb.[7] The bread buns, ciabatta and croissants were cut into slices of 2 cm. The crumb was cut into cylinders with a diameter of 3 cm. The bread cylinders were analysed using double compression with a flat, circular compression plate probe (∅◙ 75 mm) and a load cell of 5 kg. The samples were compressed up to 80% strain at a compression speed of 2 mm s^{-1}. A strain of 80% was used as it better correlates to sensory perception compared to the more generally used 40% strain.[35] The measurement was repeated to obtain ten replicates. Crust hardness (g) was assessed with the Puncture Test using the TA.XT Plus Texture Analyser (Stable Micro Systems Ltd., Surrey, UK). A 2 mm diameter cylindrical probe was used at a descending speed of 40 mm s^{-1}. Probe size and speed were chosen to simulate the puncturing and closing speed of the front teeth.[36] Ten replicates for the bottom crust and ten replicates for the top crust were performed for each bread type.

The maximum height of half a portion of bread was determined four times using a ruler. The volume (cm^3) and density (g cm^{-3}) of the half portion samples were measured in duplicate using rapeseed displacement according to the AACC method 10-05.01.[37] The crust to crumb ratio of the different bread types was determined by manually separating the crust from the crumb. Crumb that could not be separated from the crust was considered to be part of the crust. The initial weight of the bread samples was measured before separation and the weight of the crust was measured after separation. Thereafter, the crust to crumb ratio was calculated as crust : crumb = $m_{\text{crust}}/(m_{\text{initial weight}} - m_{\text{crust}})$. The measurement was performed in triplicate.

The moisture content (MC) was measured of the bite size pieces. The pieces were placed on aluminium dishes and were weighed pre and post drying at 110 °C for 20 h. The MC (wt%) was calculated based on a wet weight basis using MC = $(m_0 - m_1)/m_0$, where m_0 is the weight before drying and m_1 is the weight after drying. Six replicates were measured. An indication of the water absorptive capacity (WAC) was measured by weighing bite size pieces of bread, submerging the samples in water for ten seconds, removing excess water by gently squeezing the sample by hand, and weighing again. The WAC (g water/g bread) was calculated using WAC = $(m_1 - m_0)/m_0$, where m_0 is the weight before submerging and m_1 is the weight after submerging in water. Four replicates were measured.

2.8 Model development

Two models predicting ER were developed using response surface methodology (RSM). The first model was based on sensory texture and the second model was based on the physical properties of the bread. Before modelling was performed, the data was checked for outliers using the 1.5x interquartile range (IQR) method, but no outliers were observed. Bootstrapping was performed for the replicate instrumental measurements of the TPA and puncture test to generate multiple means (36) needed to give good parameter estimations during modelling. This was done for the ER and sensory data as well to obtain multiple means. As little replicate data was present on WAC, density, and crust to crumb ratio, bootstrapping would not yield an improved estimation of the mean and it was thus decided to use the average values. The RSM models included linear, interaction and quadratic terms. Parameter reduction of the models was done using stepwise removal of terms based on *P* values with $\alpha_{\text{in}} = 0.01$ and $\alpha_{\text{out}} = 0.15$. A stricter α_{in} than the usual 0.15 was used and non-hierarchal models were accepted to decrease the number of insignificant terms in the models[38] and to reduce multicollinearity of terms (assessed by the variance inflation factor (VIF)). To investigate how well the models predict the measured ER of the breads, the observed *versus* the predicted ER were plotted based on leave-one-out cross validation (LOOCV) and a residual plot was made. Moreover, R^2, adequate precision, residual sum of squares (rSS), predicted residual sum of squares (PRESS), Bayesian information critirion (BIC), and Akaike's information criterion (AICc) were calculated.

2.9 Statistical analysis

One video recording of one of the participants failed. Therefore, the oral processing behaviour of two samples (ciabatta and brown bread) from one participant were not obtained. These missing values (bites, chews and duration) were imputed with multivariate imputation by chained equations using the package "mice" in *R*.[39] The oral processing characteristics, sensory texture, and physical properties of the breads were compared using repeated-measures ANOVA and Tukey *post-hoc* analyses. Multiple factor analysis (MFA) for oral processing characteristics, sensory texture and physical properties was performed for visual interpretation. Pearson's correlations were used to determine relationships between ER and the oral processing characteristics, sensory texture and physical properties. R version 4.1.1 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria) and the packages "rstatix", "emmeans", "FactoMineR", and "factoextra"[40] were used to perform all statistical tests. *P* values of <0.05 were considered as statistically significant.

3. Results

3.1 Oral processing behaviour

The slices of bread were consumed the slowest, followed by the hard buns (Fig. 1). The croissant and the soft white buns were consumed the fastest. The bread type consumed with the lowest ER (whole meal bread) was 40% slower than the bread type consumed with the fastest ER (soft white bun) ($P < 0.001$). The oral processing characteristics can be found in Table 3. The bread slices were consumed with more chews per gram, and longer OSE than the soft buns, ciabatta and croissant (all $P < 0.05$). In addition, the slices were consumed with smaller bites sizes expressed in grams compared to the other breads

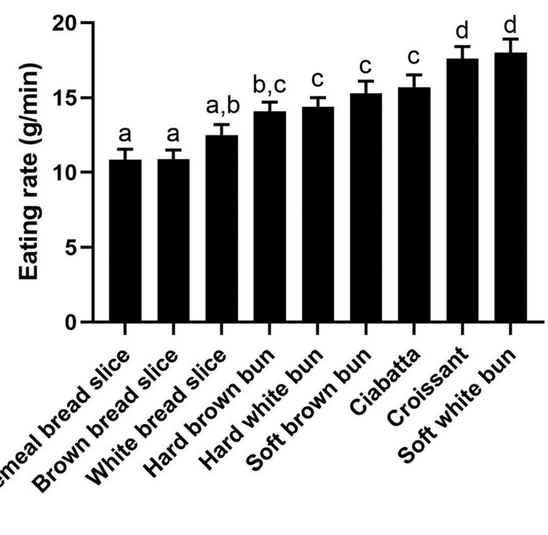

Fig. 1 Eating rate (g min^{-1}) of the bread types. Error bars represent the standard error of the mean. Different lower-case letters indicate significant differences between the means ($p < 0.05$).

Table 3 Oral processing characteristics, sensory texture and physical properties of the breads. For all the oral processing behaviour and sensory texture ratings n = 36, for the geometrical properties n = 2, crust : crumb ratio n = 3, textural properties of the crumb n = 10 and of the crust n = 20, moisture content n = 6 and water absorptive capacity n = 4

	Wholemeal bread slice	Brown bread slice	White bread slice	Hard brown bun	Hard white bun	Ciabatta	Soft brown bun	Soft white bun	Croissant	P
Oral processing behaviour[a]										
Eating rate (g min^{-1})	11 ± 1	11 ± 1	12 ± 1	14 ± 1	14 ± 1	16 ± 1	15 ± 1	18 ± 1	18 ± 1	**<0.001**
Bite weight (g)	3.8 ± 0.2	3.9 ± 0.3	3.8 ± 0.2	5.5 ± 0.2	5.6 ± 0.2	5.8 ± 0.3	5.8 ± 0.3	5.8 ± 0.3	5.2 ± 0.3	**<0.001**
Bite volume (cm^3)	23 ± 1	23 ± 1	23 ± 1	24 ± 1	21 ± 1	22 ± 1	35 ± 2	35 ± 2	31 ± 2	**<0.001**
Chews per gram (g^{-1})	8.5 ± 0.7	7.9 ± 0.5	6.8 ± 0.5	5.6 ± 0.3	5.5 ± 0.3	5.2 ± 0.3	5.6 ± 0.5	5.0 ± 0.4	4.8 ± 0.3	**<0.001**
Chews per bite (–)	32 ± 3	31 ± 3	25 ± 3	31 ± 3	31 ± 0	23 ± 2	33 ± 4	29 ± 3	24 ± 2	**<0.001**
OSE (s g^{-1})	5.8 ± 0.4	5.5 ± 0.3	4.8 ± 0.3	4.0 ± 0.2	4.0 ± 0.2	3.8 ± 0.2	3.9 ± 0.3	3.4 ± 0.2	3.2 ± 0.2	**<0.001**
Chewing frequency (s^{-1})	1.47 ± 0.03	1.43 ± 0.02	1.41 ± 0.03	1.37 ± 0.03	1.36 ± 0.03	1.38 ± 0.02	1.42 ± 0.03	1.46 ± 0.02	1.48 ± 0.03	**<0.001**
Saliva incorporation (g per g)	0.17 ± 0.01	0.18 ± 0.01	0.17 ± 0.01	0.21 ± 0.01	0.20 ± 0.01	0.20 ± 0.0	0.15 ± 0.01	0.17 ± 0.01	0.21 ± 0.01	**<0.001**
Sensory texture[a]										
Hardness crumb	19 ± 2	24 ± 3	16 ± 2	32 ± 3	30 ± 3	31 ± 3	16 ± 2	11 ± 2	12 ± 2	**<0.001**
Dryness crumb	44 ± 4	40 ± 4	27 ± 4	30 ± 3	25 ± 3	20 ± 3	32 ± 4	23 ± 3	13 ± 2	**<0.001**
Chewiness crumb	35 ± 4	34 ± 5	28 ± 4	38 ± 4	43 ± 4	38 ± 4	32 ± 4	30 ± 4	16 ± 3	**<0.001**
Adhesiveness crumb	29 ± 4	29 ± 4	44 ± 4	40 ± 4	49 ± 4	40 ± 3	49 ± 4	54 ± 4	38 ± 4	**<0.001**
Compactness crumb	33 ± 4	32 ± 4	37 ± 4	47 ± 3	47 ± 4	41 ± 4	44 ± 4	43 ± 4	20 ± 4	**<0.001**
Hardness crust	43 ± 4	50 ± 4	46 ± 4	70 ± 3	69 ± 3	58 ± 3	9 ± 1	7 ± 1	19 ± 3	**<0.001**
Crispiness crust	20 ± 3	19 ± 3	19 ± 3	69 ± 3	66 ± 3	57 ± 4	12 ± 3	13 ± 3	59 ± 4	**<0.001**
Crumbliness crust	22 ± 3	21 ± 3	19 ± 3	52 ± 4	58 ± 4	33 ± 4	9 ± 1	10 ± 2	80 ± 3	**<0.001**
Physical properties[b]										
Maximum height (cm)	1.3 ± 0.0	1.4 ± 0.1	1.3 ± 0.1	4.9 ± 0.2	5.1 ± 0.4	5.8 ± 0.2	5.1 ± 0.2	5.0 ± 0.2	5.0 ± 0.2	**<0.001**
Volume (cm^3)	113 ± 1	112 ± 5	106 ± 2	168 ± 7	144 ± 2	158 ± 3	154 ± 5	156 ± 0	148 ± 2	**<0.001**
Density (g cm^{-3})	0.17 ± 0.00	0.16 ± 0.01	0.16 ± 0.00	0.23 ± 0.00	0.26 ± 0.00	0.29 ± 0.00	0.16 ± 0.01	0.16 ± 0.01	0.17 ± 0.00	**<0.001**
Crust : crumb ratio (–)	0.77 ± 0.03	0.75 ± 0.03	0.86 ± 0.05	1.66 ± 0.04	1.61 ± 0.32	1.5 ± 0.17	0.84 ± 0.07	0.98 ± 0.06	1.72 ± 0.27	**<0.001**
Hardness crumb (g)	1360 ± 163	1088 ± 180	868 ± 108	1671 ± 284	1755 ± 369	2413 ± 1107	1214 ± 131	1091 ± 241	913 ± 350	**<0.001**
Springiness crumb (–)	0.98 ± 0.02	0.98 ± 0.02	1.01 ± 0.11	0.50 ± 0.04	0.72 ± 0.09	0.8 ± 0.12	0.53 ± 0.07	0.61 ± 0.11	0.93 ± 0.03	**<0.001**
Cohesiveness crumb (–)	0.68 ± 0.01	0.69 ± 0.01	0.68 ± 0.02	0.62 ± 0.01	0.68 ± 0.02	0.7 ± 0.03	0.64 ± 0.02	0.61 ± 0.02	0.61 ± 0.05	**<0.001**
Chewiness crumb (g)	906 ± 93	730 ± 106	598 ± 79	517 ± 106	845 ± 131	1274 ± 469	409 ± 48	397 ± 64	517 ± 215	**<0.001**
Resilience crumb (–)	0.26 ± 0.00	0.26 ± 0.01	0.24 ± 0.01	0.24 ± 0.01	0.26 ± 0.01	0.29 ± 0.01	0.25 ± 0.01	0.22 ± 0.01	0.2 ± 0.02	**<0.001**
Adhesiveness crumb (g s)	0.24 ± 0.09	0.19 ± 0.17	0.22 ± 0.1	−2.96 ± 2.93	−1.91 ± 2.46	−0.61 ± 2.26	0.11 ± 0.31	−0.11 ± 0.60	0.15 ± 0.08	**<0.001**
Hardness crust (g)	986 ± 360	872 ± 385	872 ± 340	817 ± 188	1140 ± 318	695 ± 186	147 ± 63	98 ± 24	185 ± 88	**<0.001**
Moisture content (wt%)	0.32 ± 0.01	0.30 ± 0.01	0.27 ± 0.01	0.26 ± 0.01	0.26 ± 0.01	0.27 ± 0.02	0.33 ± 0.03	0.29 ± 0.01	0.17 ± 0.02	**<0.001**
WAC (g_{water}/g_{bread})	1.06 ± 0.13	1.01 ± 0.13	0.85 ± 0.02	0.98 ± 0.14	1.01 ± 0.03	0.6 ± 0.04	0.8 ± 0.03	1.1 ± 0.02	0.43 ± 0.03	**<0.001**

OSE: oro-sensory exposure; WAC: water absorptive capacity. Bold values denote statistical significance at the $p < 0.05$ level. [a] Values are mean ± SEM. [b] Values are mean ± SD.

(3.8–3.9 g *vs.* 5.2–5.8 g, $P < 0.001$). Bite size expressed in volume was smaller for the bread slices and hard buns compared to the soft buns and croissant (21–24 cm^3 *vs.* 31–35 cm^3, $P < 0.001$). The saliva incorporation per gram was higher for the harder breads (hard buns and ciabatta) compared to the slices and soft buns ($P < 0.05$), with an exception for the croissant. The chewing frequency by which bread was consumed was quite similar for all the bread types. The liking of the breads can be found in Table 1 of the ESI.†

3.2 Relationships between eating rate, oral processing, sensory texture and physical properties

The relationships between oral processing behaviour, sensory texture and the physical properties were visualized using MFA (Fig. 2). The first two dimensions explain together 70.9% of the variance. Visual inspection of the MFA showed that ER was positively related with bite weight, sensory measured crumb adhesiveness, maximum height, and volume. ER was negatively related with chews per gram, chews per bite, OSE, sensory measured crumb dryness, and the physical properties WAC, moisture content, crust hardness, crumb cohesiveness and springiness. The individual plot of the MFA shows that the bread types can be clustered into three groups: bread slices, hard buns and soft buns (Fig. 2B). The bread slices were characterized by lower ER, high OSE, high chews per gram, high sensory ratings for crumb dryness, and low height. The hard buns were characterized by high density, high crumb hardness and low adhesiveness from the physical measurements. The soft bun had high ER, bite volume and low sensory rated and physical measured hardness (crust and crumb) and chewiness. Pearson correlation coefficients for ER (Table 2 of the ESI†) had similar results as the MFA.

The correlations between sensory and physical measurement of the hardness of crust, sensory and physical hardness of the crumb, and sensory dryness of the crumb and WAC were high ($\rho \geq 0.69$, $P < 0.05$; Table 4). For chewiness, adhesiveness and compactness of the crumb the correlations between sensory and TPA measurements were low ($\rho \leq 0.49$, $P \geq 0.18$).

3.3 Prediction modelling

The sensory texture model as well as the model based on physical properties were able to predict ER. The coefficient estimates of the models indicate the magnitude of effect of the model terms on the predicted ER in the model (Table 5). The fit statistics and model comparison statistics of the sensory texture model and the model based on physical properties model are presented in Table 6. For both models the predicted

Table 4 Pearson correlations coefficients of average values of sensory texture and physical properties

Sensory texture	Physical properties	Pearson correlation coefficient	*P*
Hardness crumb	Hardness crumb (g)	0.80	**0.01**
Dryness crumb	WAC (g_{water}/g_{bread})	0.69	**0.04**
Chewiness crumb	Chewiness crumb (g)	0.49	0.18
Adhesiveness crumb	Adhesiveness crumb (g s)	−0.19	0.62
Compactness crumb	Density (g cm^{-3})	0.45	0.23
Hardness crust	Hardness crust (g)	0.89	**0.001**

WAC: water absorptive capacity. Bold values denote statistical significance at the $p < 0.05$ level

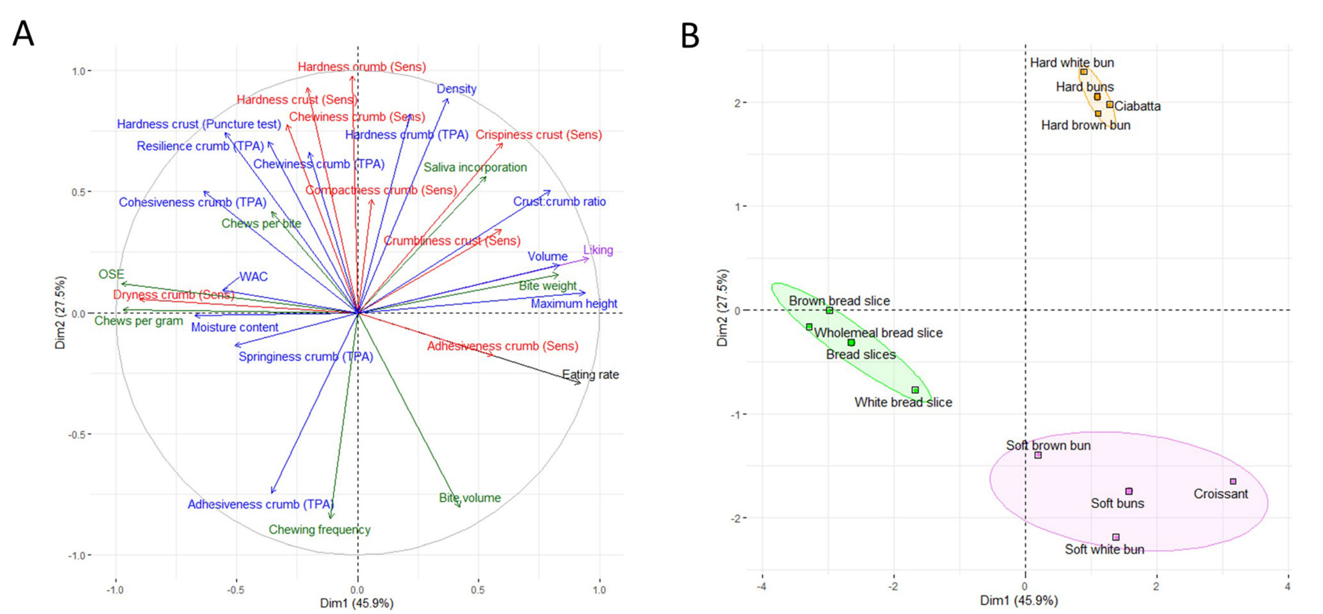

Fig. 2 Plots of multiple factorial analysis (MFA). In the correlation circle (a) the correlation of eating rate (black), oral processing characteristics (green), sensory texture (sens; red), and physical properties (blue) with the first two dimension of the MFA is showed. In the individual factor map (b) the projections of bread types are showed with 95% confidence ellipses for the grouped bread slices (green), hard buns (orange) and soft buns (purple). OSE oro-sensory exposure time, TPA texture profile analysis, WAC water absorptive capacity.

Table 5 Coefficient estimates of the factors in the sensory texture model and model of the physical properties developed with response surface methodology. The coefficient estimates indicate the magnitude of effect of the model terms on the predicted ER in the model. The coefficients are based on the normalised factor values (coded). Values are means ± SEM

	Sensory texture model		Physical properties model	
	Model terms	Coefficient estimate	Model terms	Coefficient estimate
Linear terms	Dryness crumb	−2.27 ± 0.18		
	Hardness crust	−1.76 ± 0.18		
Exponential terms	Crispiness crust × Crumbliness crust	−2.88 ± 0.36	Springiness crumb × WAC	−44.40 ± 2.06
	Hardness crumb × Hardness crust	1.40 ± 0.38	Cohesiveness crumb × WAC	−29.38 ± 1.77
	Adhesiveness crumb × Crumbliness crust	−1.46 ± 0.31	Cohesiveness crumb × MC	9.97 ± 2.21
			Maximum height × Adhesiveness crumb	5.88 ± 0.19
			Crust : crumb ratio × Adhesiveness crumb	−4.29 ± 0.41
Quadratic terms	Hardness crust × Hardness crust	2.41 ± 0.34		
	Dryness crumb × Dryness crumb	1.91 ± 0.32		

WAC: water absorptive capacity; MC: moisture content

Table 6 Fit and model comparison statistics of the sensory texture model and model of the physical properties developed using response surface methodology. For all terms in the sensory texture model and the model based on physical properties the VIF was between 2.0 and 6.1, indicating the presence of multi-collinearity at a tolerable level (VIF < 10)

	Sensory texture model	Physical properties model
Fit		
R^2	0.89	0.91
Adjusted R^2	0.89	0.91
Predicted R^2	0.89	0.91
Adeq precision	66	75
RSS	239	195
Model comparison		
Number of model terms	7	5
PRESS	252	203
−2 log Likelihood	821	755
BIC	868	790
AICc	838	768

Adeq precision: adequate precision, RSS: residual sum of squares, PRESS: predicted residual sum of squares, BIC: Bayesian information critirion, AICc: Akaike's information criterion

R^2 is in reasonable agreement (Δ <0.2) with the adjusted R^2. In addition, the adequate precision indicates an adequate signal to noise ratio (>4). The model based on physical properties had slightly better fit and model comparison statistics than the sensory texture model. The visualization of the internal validation can be found in Fig. 1 of the ESI.† The equations of the model terms related to the actual factors can be found in Table 3 of the ESI.†

The sensory model included seven model terms, of which two linear, two quadratic and three interactions. The largest coefficient estimate of the sensory texture model was the interaction term crispiness crust × crumbliness crust (negative estimate). Hardness crust and dryness crumb were both in the model as negative linear term and as positive quadratic term. When adding measured range of hardness crust and dryness crumb (0 to 100) in the equations of the actual factors (Table 3 of the ESI†), the effect of hardness crust and dryness crumb on ER is overall negative.

The model of the physical properties of the bread included five model terms which were all interactions. The largest coefficient estimates of the model with the physical properties were springiness crumb × WAC (negative estimate), followed by cohesiveness crumb × WAC (negative estimate). The surface plots of the interactions can be found in Fig. 2 and 3 of the ESI.†

4. Discussion

In this study, bread slices had the lowest ER, followed by hard buns, while soft buns and croissants had the highest ER. For the sensory texture, ER was positively correlated with crumb adhesiveness and negatively correlated with crumb dryness. For the physical properties, ER was positively correlated with height and volume, and ER negatively correlated with crumb cohesiveness and crust hardness. The ER of bread could be predicted from its sensory texture and from its physical properties. The model based on the physical properties had a slightly higher accuracy compared to the model based on sensory texture.

Relevant differences in ER were found in this study, where bread slices had ER of 11 g min^{-1} and soft buns and croissants had the highest ER of 15–18 g min^{-1}. Similar trends were found by Van den Boer *et al.* (2017) who observed the lowest ER for brown bread slices and the highest ER for croissants.[41] Texture induced reductions of ER by 20% can lead to a 10–15% reduction in *ad libitum* energy intake.[18,42] The study of Bolhuis *et al.* (2014) showed that a lunch consisting out of hamburgers with hard buns and hard rice salad had a 32% lower ER and 13% lower energy intake compared to the lunch with hamburgers with soft buns and soft rice salad.[12] In the present study, a decrease in ER up to 40% between breads was found. This is likely to affect energy intake and satiety in realistic settings. Therefore, switching to breads with low ERs could be an effective strategy to modify energy intake.

The ER of bread is the result of the interplay between crust texture (*i.e.* hardness), crumb properties (*i.e.* dryness, adhesiveness and cohesiveness) and bread dimensions (*i.e.* height and volume).[25] A clear distinction in ER was seen between the slices, soft buns and hard buns. The differences between the slices and buns are most likely explained by the automatically smaller bite sizes consumed due to the dimensions of the slices. Previous research also showed that geometrical properties have a relevant effect on ER.[43–48] Individuals adjust their bite sizes to a maximal but comfortable length of the food in their oral cavity.[49] Therefore, a shape with increased height is automatically consumed with larger bite sizes in many cases.[18] Besides the smaller bite sizes by which slices are consumed, the lower ER of the slices compared to other breads is also characterized by the high rated dryness of the bread slices' crumb and lower moisture content. Dryer foods with lower moisture contents need to be lubricated to a larger extend to form a swallowable bolus.[50] Saliva is needed to migrate into the food where it moistens and softens, helping to agglomerate particles to form a compact bolus. With lower initial lubrication, this process takes longer and thereby decreasing the ER.[51,52]

The bread slices had a lower crust to crumb ratio compared to the buns. This means that characteristics of the crumb will have a relatively high impact on the ER of slices, whereas the crust has a relatively high impact on the ER of buns. Indeed, the differences between hard and soft buns in ER was mainly based on the hardness of the crust and less on their crumb characteristics. With the presence of thick, hard and dry crust, the number of chews, chewing time and muscle activities increases considerably.[53,54] It takes a longer time for a harder and dry crust to be fractured into smaller particle sizes to facilitate sufficient particle softening, structure breakdown, and bolus lubrication leading to a lower ER.[50,55]

RSM modelling was performed to determine which sensory textures and physical properties are most influential in determining the ER. With modelling, it can be found which factors have the most influence on ER, it includes interactions and non-linear relations, and the method filters out the measures that have multicollinearity.[56] The model based on physical properties performed better than the sensory model as illustrated by the lower AICc value (it gives a better fit with less model terms). This is beneficial for its application since sensory evaluation is more expensive and time consuming,[29,31] while instrumental/physical measurements are less costly and more precise.[30] A model including both sensory and physical data to predict ER was developed, but not presented in this paper. The combined model included more model terms (n = 8) than the separate models and only had a slightly better fit (*e.g.*, adjusted R^2 and predicted R^2 were both 0.92 compared to 0.91 of the physical properties model). Three of the model terms were interactions between sensory texture and physical properties, and the other model terms provided little additional information as most of these terms were already included in the separate models. Therefore, we reported two separate models—one based on sensory texture and one on physical properties—as these provide the most relevant and clear insights.

The predictions included different model terms in the two models, where dryness, hardness and crumbliness were most prominent in the sensory model, and adhesiveness, cohesiveness and WAC were most prominent in the model based on physical properties. A possible explanation why different terms are included in the two models, might be that the physical properties do not always well represent the associated sensory evaluations[57] as shown in the correlations between physical and sensory measurements in the results. This study showed that related terms measured using sensory and physical methods are related for a few attributes, including hardness and dryness/water absorption, but not for adhesiveness, chewiness, and compactness/density. The physical properties partly cover the sensory evaluations but also included two additional properties: density and dimensional measures. This could explain the different selection of terms that are included in both models.

Most of the included model terms in the models were interactions. This might be because texture properties are intertwined and cannot be modified in isolation. An example of a strong interaction is the interaction between crumb springiness and WAC. A more springy and elastic food decreases ER.[7,58,59] Higher WAC might lead to more absorption of saliva into the food. Therefore, more saliva and time might be needed for softening and agglomeration of the food particles to form a compact bolus, and thereby decreasing the ER.[51,52] In the interaction, the lowest ER is reached with both a low WAC and low springiness of the crumb, while the highest ER is reached with a low springiness and high WAC (see Fig. 3 in ESI†). The interaction between WAC and springiness might have contributed to the hard buns to have a higher ER than the bread slices. Due to the high impact of these interactions on predicting ER, more research is needed to better understand the meaning of these interactions on oral processing and ER of various food textures.

Since breads are often consumed as a composite food,[52] for future research investigating the oral processing, ER, energy intake and satiety of composite bread products should be considered. The condiments or fillings added to the breads can increase initial lubrication and might be compensating for the dryness of the bread.[52] A recent study showed that addition of margarine on bread slices made the bread samples perceived as less dry and speeded up ER in general. However, texture differences between different types of bread samples were largely retained in perceived hardness, denseness, and chewiness.[48] A recent study showed that the total ER of a meal or composite food is usually an add up of ER of the separate food items.[13] This indicates that changing ER by texture modifications of the breads is expected to change the ER of the total composite foods and thereby the food intake. However more research is needed for meals and composite foods and its effect on ER, energy intake and satiety.

The results provide guidance on how to modify the physical properties to reduce the ER of bread. However, for practical application, hedonics must be considered. Maintaining comparable levels of acceptability and liking when modifying texture can be challenging. Therefore, the intertwined effects of liking (assessed by a larger group of consumers) in relation to texture and ER should be investigated further.

To conclude, bread slices had the lowest ER, followed by hard buns, whereas soft buns had the highest ER. Buns have larger crust to crumb ratio and modifications on crusts will have relatively high impact on ER, whereas crumb modifications will contribute more to ER of slices. The ER of bread can be predicted from both sensory measured texture and its physically properties. Most of the sensory measured textures and physical properties showed interaction effects in the RSM models, which highlights the complexity of the intertwined textural model terms on oral processing characteristics. The model based on the physical properties was slightly more accurate in predicting ER in this study, where products from the same food category were compared. This means that for predicting the ER of breads, using only physical measures is sufficient and saves time and costs compared to more laborious sensory evaluations. However, the outcomes of both RSM models and the correlations can be used to modify bread texture to steer ER. The insights from the relationships from both the sensory texture and physical measures can be used to modify the texture of breads, to effectively decrease ER and eventually help to prevent overconsumption.

Author contributions

Lise A.J. Heuven: conceptualization, methodology, investigation, formal analysis, visualization, writing – original draft, writing – review & editing. Matthijs Dekker: conceptualization, supervision, methodology, writing – review & editing. Stefano Renzetti: conceptualization, supervision, methodology, writing – review & editing. Dieuwerke P. Bolhuis: conceptualization, supervision, methodology, project administration, writing – review & editing, funding acquisition.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of 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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References

1 E. Pineda, L. M. Sanchez-Romero, M. Brown, A. Jaccard, J. Jewell, G. Galea, L. Webber and J. Breda, Forecasting future trends in obesity across Europe: the value of improving surveillance, *Obes. Facts*, 2018, **11**, 360–371.

2 E. Robinson, E. Almiron-Roig, F. Rutters, C. de Graaf, C. G. Forde, C. Tudur Smith, S. J. Nolan and S. A. Jebb, A systematic review and meta-analysis examining the effect of eating rate on energy intake and hunger, *Am. J. Clin. Nutr.*, 2014, **100**, 123–151.

3 G. Argyrakopoulou, S. Simati, G. Dimitriadis and A. Kokkinos, How important is eating rate in the physiological response to food intake, control of body weight, and glycemia?, *Nutrients*, 2020, **12**, 1734.

4 E. M. Krop, M. M. Hetherington, C. Nekitsing, S. Miquel, L. Postelnicu and A. Sarkar, Influence of oral processing on appetite and food intake - a systematic review and meta-analysis, *Appetite*, 2018, **125**, 253–269.

5 K. Gonzalez-Estanol, M. Libardi, F. Biasioli and M. Stieger, Oral processing behaviours of liquid, solid and composite foods are primarily driven by texture, mechanical and lubrication properties rather than by taste intensity, *Food Funct.*, 2022, **13**, 5011–5022.

6 C. Forde, N. van Kuijk, T. Thaler, C. de Graaf and N. Martin, Texture and savoury taste influences on food intake in a realistic hot lunch time meal, *Appetite*, 2013, **60**, 180–186.

7 M. S. M. Wee, A. T. Goh, M. Stieger and C. G. Forde, Correlation of instrumental texture properties from textural profile analysis (TPA) with eating behaviours and macronutrient composition for a wide range of solid foods, *Food Funct.*, 2018, **9**, 5301–5312.

8 D. P. Bolhuis, C. M. Lakemond, R. A. de Wijk, P. A. Luning and C. de Graaf, Both longer oral sensory exposure to and higher intensity of saltiness decrease ad libitum food intake in healthy normal-weight men, *J. Nutr.*, 2011, **141**, 2242–2248.

9 L. Engelen, A. Fontijn-Tekamp and A. van der Bilt, The influence of product and oral characteristics on swallowing, *Arch. Oral Biol.*, 2005, **50**, 739–746.

10 E. C. Ketel, M. G. Aguayo-Mendoza, R. A. de Wijk, C. de Graaf, B. Piqueras-Fiszman and M. Stieger, Age, gender, ethnicity and eating capability influence oral processing behaviour of liquid, semi-solid and solid foods differently, *Food Res. Int.*, 2019, **119**, 143–151.

11 M. G. Aguayo-Mendoza, E. C. Ketel, E. van der Linden, C. G. Forde, B. Piqueras-Fiszman and M. Stieger, Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties, *Food Qual. Prefer.*, 2019, **71**, 87–95.
12 D. P. Bolhuis, C. G. Forde, Y. Cheng, H. Xu, N. Martin and C. de Graaf, Slow food: sustained impact of harder foods on the reduction in energy intake over the course of the day, *PLoS One*, 2014, **9**, e93370.
13 L. A. Heuven, K. de Graaf, C. G. Forde and D. P. Bolhuis, Al dente or well done? How the eating rate of a pasta dish can be predicted by the eating rate of its components, *Food Qual. Prefer.*, 2023, 104883.
14 R. Janani, V. W. K. Tan, A. T. Goh, M. J. Y. Choy, A. J. Lim, P. S. Teo, M. Stieger and C. G. Forde, Independent and combined impact of texture manipulation on oral processing behaviours among faster and slower eaters, *Food Funct.*, 2022, **13**, 9340–9354.
15 M. P. Lasschuijt, M. Mars, M. Stieger, S. Miquel-Kergoat, C. de Graaf and P. Smeets, Comparison of oro-sensory exposure duration and intensity manipulations on satiation, *Physiol. Behav.*, 2017, **176**, 76–83.
16 K. McCrickerd, C. M. Lim, C. Leong, E. M. Chia and C. G. Forde, Texture-based differences in eating rate reduce the impact of increased energy density and large portions on meal size in adults, *J. Nutr.*, 2017, **147**, 1208–1217.
17 A. C. Mosca, A. P. Torres, E. Slob, K. de Graaf, J. A. McEwan and M. Stieger, Small food texture modifications can be used to change oral processing behaviour and to control ad libitum food intake, *Appetite*, 2019, **142**, 104375.
18 D. P. Bolhuis and C. G. Forde, Application of food texture to moderate oral processing behaviors and energy intake, *Trends Food Sci. Technol.*, 2020, **106**, 445–456.
19 S. Cauvain, in *Technology of breadmaking*, Springer, 2015, pp. 1–22.
20 C. van Rossum, E. Buurma-Rethans, C. Dinnissen, M. Beukers, H. Brants and M. Ocké, *The diet of the Dutch: results of the Dutch National Food Consumption Survey 2012–2016*, 2020.
21 A. Cust, M. Skilton, M. Van Bakel, J. Halkjaer, A. Olsen, C. Agnoli, T. Psaltopoulou, E. Buurma, E. Sonestedt and M. Chirlaque, Total dietary carbohydrate, sugar, starch and fibre intakes in the European Prospective Investigation into Cancer and Nutrition, *Eur. J. Clin. Nutr.*, 2009, **63**, S37–S60.
22 F. Le Bleis, L. Chaunier, H. Chiron, G. Della Valle and L. Saulnier, Rheological properties of wheat flour dough and French bread enriched with wheat bran, *J. Cereal Sci.*, 2015, **65**, 167–174.
23 C. Primo-Martín, G. Van Dalen, M. Meinders, A. Don, R. Hamer and T. Van Vliet, Bread crispness and morphology can be controlled by proving conditions, *Food Res. Int.*, 2010, **43**, 207–217.
24 M. Kinner, R. Rüegg, C. A. Weber, J. Buchli, L. Durrer and N. Müller, Impact of selected baking and vacuum cooling parameters on the quality of toast bread, *J. Food Sci. Technol.*, 2021, 1–9.
25 J. Gao and W. Zhou, Oral processing of bread: Implications of designing healthier bread products, *Trends Food Sci. Technol.*, 2021, **112**, 720–734.
26 S. Jourdren, M. Panouille, A. Saint-Eve, I. Deleris, D. Forest, P. Lejeune and I. Souchon, Breakdown pathways during oral processing of different breads: impact of crumb and crust structures, *Food Funct.*, 2016, **7**, 1446–1457.
27 J. Gao, J. X. Wong, J. C.-S. Lim, J. Henry and W. Zhou, Influence of bread structure on human oral processing, *J. Food Eng.*, 2015, **167**, 147–155.
28 P. Yu, M. Y. Low and W. Zhou, Design of experiments and regression modelling in food flavour and sensory analysis: a review, *Trends Food Sci. Technol.*, 2018, **71**, 202–215.
29 K. Nishinari and Y. Fang, Perception and measurement of food texture: Solid foods, *J. Texture Stud.*, 2018, **49**, 160–201.
30 K. Nishinari, Y. Fang and A. Rosenthal, Human oral processing and texture profile analysis parameters: Bridging the gap between the sensory evaluation and the instrumental measurements, *J. Texture Stud.*, 2019, **50**, 369–380.
31 A. J. Rosenthal, Relation between instrumental and sensory measures of food texture, in *Food texture: Measurement and perception*, 1999, pp. 1–17.
32 C. Forde, N. van Kuijk, T. Thaler, C. de Graaf and N. Martin, Oral processing characteristics of solid savoury meal components, and relationship with food composition, sensory attributes and expected satiation, *Appetite*, 2013, **60**, 208–219.
33 T. K. Koo and M. Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, *J. Chiropr. Med.*, 2016, **15**, 155–163.
34 W. Edgar, Saliva: its secretion, composition and functions, *Br. Dent. J.*, 1992, **172**, 305–312.
35 S. M. Fiszman, A. Salvador and P. Varela, Methodological developments in bread staling assessment: application to enzyme-supplemented brown pan bread, *Eur. Food Res. Technol.*, 2005, **221**, 616–623.
36 R. Altamirano-Fortoul, I. Hernando and C. M. Rosell, Texture of bread crust: puncturing settings effect and its relationship to microstructure, *J. Texture Stud.*, 2013, **44**, 85–94.
37 M. S. Caley, S. Park and O. K. Chung, Comparison of loaf-volume measuring methods: Rapeseed displacement vs. laser sensor, *AACC International Meeting*, 2005, poster paper no. 111.
38 W. Wang, J. Sun, J. Liu, J. Zhao, J. Pei and J. Wang, Introducing Non-Hierarchical RSM and MIGA for Performance Prediction and Optimization of a Centrifugal Pump under the Nominal Condition, *Processes*, 2022, **10**, 1529.
39 S. Van Buuren and K. Groothuis-Oudshoorn, mice: Multivariate imputation by chained equations in R, *J. Stat. Softw.*, 2011, **45**, 1–67.
40 A. Kuznetsova, P. B. Brockhoff and R. H. Christensen, lmerTest package: tests in linear mixed effects models, *J. Stat. Softw.*, 2017, **82**, 1–26.

41 J. van den Boer, M. Werts, E. Siebelink, C. de Graaf and M. Mars, The availability of slow and fast calories in the Dutch diet: the current situation and opportunities for interventions, *Foods*, 2017, **6**, 87.

42 L. A. Heuven, M. van Bruinessen, C. S. Tang, M. Stieger, M. P. Lasschuijt and C. G. Forde, Consistent effect of eating rate on food and energy intake across twenty-four ad libitum meals, *Br. J. Nutr.*, 2024, 1–12.

43 A. van Eck, A. van Stratum, D. Achlada, B. Goldschmidt, E. Scholten, V. Fogliano, M. Stieger and D. Bolhuis, Cracker shape modifies ad libitum snack intake of crackers with cheese dip, *Br. J. Nutr.*, 2020, **124**, 988–997.

44 A. van Eck, C. Wijne, V. Fogliano, M. Stieger and E. Scholten, Shape up! How shape, size and addition of condiments influence eating behavior towards vegetables, *Food Funct.*, 2019, **10**, 5739–5751.

45 P. L. Weijzen, D. G. Liem, E. Zandstra and C. De Graaf, Sensory specific satiety and intake: The difference between nibble-and bar-size snacks, *Appetite*, 2008, **50**, 435–442.

46 K. Kohyama, Y. Nakayama, I. Yamaguchi, M. Yamaguchi, F. Hayakawa and T. Sasaki, Mastication efforts on block and finely cut foods studied by electromyography, *Food Qual. Prefer.*, 2007, **18**, 313–320.

47 D. G. Liem and C. G. Russell, Supersize me. Serving carrots whole versus diced influences children's consumption, *Food Qual. Prefer.*, 2019, **74**, 30–37.

48 D. P. Bolhuis, M. Dekker and S. Renzetti, Spread it on thick? Relative effects of condiment addition and slice thickness on eating rate of bread, *Food Funct.*, 2024, **15**, 3838–3847.

49 S. C. Hutchings, J. E. Bronlund, R. G. Lentle, K. D. Foster, J. R. Jones and M. P. Morgenstern, Variation of bite size with different types of food bars and implications for serving methods in mastication studies, *Food Qual. Prefer.*, 2009, **20**, 456–460.

50 J. B. Hutchings and P. Lillford, The perception of food texture–the philosophy of the breakdown path, *J. Texture Stud.*, 1988, **19**, 103–115.

51 A. van Eck, E. Franks, C. J. Vinyard, V. Galindo-Cuspinera, V. Fogliano, M. Stieger and E. Scholten, Sauce it up: influence of condiment properties on oral processing behavior, bolus formation and sensory perception of solid foods, *Food Funct.*, 2020, **11**, 6186–6201.

52 A. van Eck and M. Stieger, Oral processing behavior, sensory perception and intake of composite foods, *Trends Food Sci. Technol.*, 2020, **106**, 219–231.

53 J. Gao, J. J.-X. Ong, J. Henry and W. Zhou, Physical breakdown of bread and its impact on texture perception: A dynamic perspective, *Food Qual. Prefer.*, 2017, **60**, 96–104.

54 C. Tournier, M. Grass, D. Zope, C. Salles and D. Bertrand, Characterization of bread breakdown during mastication by image texture analysis, *J. Food Eng.*, 2012, **113**, 615–622.

55 M.-L. Jalabert-Malbos, A. Mishellany-Dutour, A. Woda and M.-A. Peyron, Particle size distribution in the food bolus after mastication of natural foods, *Food Qual. Prefer.*, 2007, **18**, 803–812.

56 D. Baş and İ. H. Boyacı, Modeling and optimization I: Usability of response surface methodology, *J. Food Eng.*, 2007, **78**, 836–845.

57 A. B. Garcia Loredo and S. N. Guerrero, Correlation between instrumental and sensory ratings by evaluation of some texture reference scales, *Int. J. Food Sci. Technol.*, 2011, **46**, 1977–1985.

58 H. Koç, E. Çakir, C. Vinyard, G. Essick, C. Daubert, M. Drake, J. Osborne and E. Foegeding, Adaptation of oral processing to the fracture properties of soft solids, *J. Texture Stud.*, 2014, **45**, 47–61.

59 E. Çakır, C. J. Vinyard, G. Essick, C. R. Daubert, M. Drake and E. A. Foegeding, Interrelations among physical characteristics, sensory perception and oral processing of protein-based soft-solid structures, *Food Hydrocolloids*, 2012, **29**, 234–245.