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Al dente or well done? How the eating rate of a pasta dish can be predicted by the eating rate of its components

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ABSTRACT

Eating rate (ER) is now recognised as an important driver of food and energy intake, and is strongly influenced by a food's texture. However, little is known about how the textures of multiple food components combined affect the ER of a composite dish. In a full cross-over study, 54 healthy participants (age: 25 ± 7 years, BMI: 22 ± 3 kg/m^2) consumed 12 different pasta dishes. The dishes comprised single penne or carrot (hard and soft; 4 samples), single penne or carrot (hard and soft) with tomato sauce (4 samples), and combined penne (hard and soft) with carrots (hard and soft) and tomato sauce (4 samples). Behavioural coding analysis was used to quantify participant ER and oral processing behaviours for each dish. Soft penne was consumed 42% faster than hard penne ($P < 0.001$) and soft carrots were consumed 94% faster than hard carrots($P < 0.001$) when presented as single foods without sauce. The addition of sauce increased ER for both penne and carrots by approximately 30% (both $P < 0.001$). For the composite dishes, the ER of the dish with soft carrot, soft penne and sauce was consumed 45% faster than the same dish with hard components ($P < 0.001$). The ER of the composite dishes could be predicted from the ER of its single components. The ER of individual components cumulatively determined the ER of the composite dish, rather than ER being driven only by the slowest dish component. These insights provide guidance on how to compose texture modified meals that moderate both ER and energy intake.

1. Introduction

Meal size is strongly influenced by an individual's eating behaviours, and these are driven by the sensory properties of the foods being consumed. Energy intake within a meal has consistently been shown to decrease when people adjust their eating rate (ER; grams of food consumed per unit of time) in response to the physical and mechanical properties of the food being consumed (Krop et al., 2018; Teo & Forde, 2020). Previous research has shown that a reduction of 20% in ER by texture manipulation can produce a 10–15% reduction in energy intake (Bolhuis & Forde, 2020; Forde, 2018).

A well-researched texture attribute that can slow the ER of food is hardness (Bolhuis & Forde, 2020), where harder foods have a smaller average bite size, require more chews per bite and have slower ER (Aguayo-Mendoza et al., 2021; Bolhuis et al., 2014; Cahayadi et al., 2020; de Lavergne et al., 2015; Doyennette et al., 2019; Forde et al., 2013b; Koç et al., 2014; Lasschuijt et al., 2017). Increasing the hardness of solid foods has been shown to reduce food intake by between 9 and 21% (Bolhuis & Forde, 2020). However, hardness is often investigated in single or model foods (Aguayo-Mendoza et al., 2019; Cahayadi et al., 2020; de Lavergne et al., 2015; Doyennette et al., 2019; Foster et al., 2006; Koç et al., 2014; Lasschuijt et al., 2017; Zijlstra, 2010), whereas during a typical meal, these foods are often consumed together as a composite dish with textures that can interact to influence oral processing behaviour and ER (van Eck & Stieger, 2020). For example, toppings, dressings, and sauces are often added to foods and have been shown to influence the rate of consumption of the carrier food (van Eck et al., 2020). The addition of condiments to foods reduces the time needed to reach a safe swallow, thereby increasing the ER (Bolhuis & Forde, 2020; Hutchings & Lillford, 1988; Janani et al., 2022; van Eck & Stieger, 2020). Several studies show that the addition of mayonnaise, butter, or margarine increases the ER by decreasing the total number of chewing cycles required (Engelen et al., 2005; Gavião et al., 2004; Janani et al., 2022; Mosca et al., 2022; van Eck et al., 2020; van Eck, Hardeman, et al., 2019; van Eck, Wijne, et al., 2019). Individuals adjust their oral processing behaviours in response to the geometrical, mechanical and lubricant properties of complex meals, wherein multiple components interact during mastication in the formation of a cohesive

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bolus for swallow (Bolhuis & Forde, 2020). Previous research have shown this using binary simplified systems (i.e. a carrier food and condiment) whereas it remains unclear how these findings would apply to multi-component dishes that better reflect real meal-time eating behaviours.

Decreasing the hardness of a meal has been shown to increase ER and promote food intake (Bolhuis et al., 2014; Forde et al., 2013b; Langlet et al., 2018; Teo et al., 2022). For example, Bolhuis et al. (2014) compared the ER and energy intake of a lunch with a hard or soft texture. The lunch consisted of hamburgers and rice salad, where the buns of the hamburgers and the rice and vegetables of the salad differed in hardness. The harder lunch meals had a 32% lower ER and 13% lower energy intake than the soft meal (Bolhuis et al., 2014). In a study with multi-component meals including potatoes, grains, fish, chicken, fruits, vegetables, sauces, and dairy products, the harder textured meals were consumed 35% slower and had 26% lower energy intake (Teo et al., 2022). Whereas the effect size is consistent across these studies, it remains unclear which texture difference or meal component is most responsible for the observed differences in eating rate. One possibility is that the slowest meal component in a composite dish largely determines the eating rate (Bolhuis & Forde, 2020). Alternatively, the combined impact of different dish components may cumulatively determine the overall ER. Knowing whether individual component or multi-component texture modifications are needed to produce consistent texture based changes in eating rate is key when designing meal textures that moderate ER.

The aim of the current study was to determine the combined impact of component texture (hardness) and sauce addition and to investigate whether the ER of a dish is better predicted by the ER of the hardest component with the lowest ER, or if there is an additive effect of components on the overall ER of the dish.

2. Methods

2.1. Design

The study had a full crossover design with twelve conditions. The twelve conditions were served as a fixed amount that allowed several bites to enable behavioural coding of oral processing behaviour. The samples are summarised in Table 1. The penne and carrots had two levels of hardness (hard or soft) and were consumed with and without sauce. Participants attended three test days. During lunch time, participants consumed four different samples. During the whole session participants were video recorded for later behavioural coding of their oral processing behaviours.

2.2. 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) males and females with European nationality and between 18 and 55 years old were included. In addition, they consume pasta with tomato sauce commonly once or more per month. Exclusion criteria were: pregnant or lactating women; smoking; braces (not including a dental wire) or oral piercing; difficulties with swallowing, chewing and/or eating in general; suffering from an endocrine or eating disorder, gastrointestinal illness or illness of the thyroid gland, respiratory disease, or diabetes; having taste or smell disorders; use of medication that may influence study outcomes; consuming on average more than 21 glasses of alcohol per week; not willing to stop using drugs during the study period (from inclusion till last test session); intensive exercising more than eight hours per week; allergies or intolerance to any ingredient of the test dishes; or do not like pasta with tomato sauce or its ingredients based on pictures (less than five on a nine point Likert scale). Participants were informed that the study aimed to investigate the sensorial properties of different pasta dishes. Participants received a monetary incentive for their participation. Participants signed an informed consent before participation. The study was approved by the Social Sciences Ethical Committee of Wageningen University and was registered at Clinical Trial registry: NCT05019872.

Participants were screened using an online questionnaire. Participants were mailed or called if more information was needed. After screening, 66 participants were recruited for participation, of which 54 completed the whole study. Twelve participants dropped out due to availability reasons and were excluded from data analysis. The 54 participants included for data analysis—of which 10 males—were 25 ± 7 years old and had an average BMI of 22 ± 3 kg/m^2 (mean ± SD).

2.3. Test food

The single ingredient samples consisted of penne or carrot with or without sauce. The penne and carrots had two levels of hardness (hard

Table 1
Weight, sensory ratings, hardness, and moisture content of the samples. Values are means ± SD.

Sample	Weight (g)	Energy density (kcal/g)	Liking	Flavour intensity rating	Hardness rating	Chewiness rating	Hardness (N)	Moisture content (wt%)
Penne								
Penne hard	37.2 ± 0.6	1.92 ± 0.03	27 ± 4	13 ± 2	26 ± 4	62 ± 8	35.7 ± 4.4	50.8 ± 0.6
Penne soft	52.4 ± 0.7	1.36 ± 0.02	32 ± 4	14 ± 2	13 ± 2	52 ± 7	26.6 ± 1.0	66.5 ± 0.5
Penne hard + sauce	47.6 ± 0.6	2.13 ± 0.003	48 ± 7	37 ± 5	24 ± 4	56 ± 8		
Penne soft + sauce	62.9 ± 1.4	1.61 ± 0.03	49 ± 7	31 ± 4	13 ± 2	44 ± 6		
P	<0.001		<0.001	<0.001	<0.001	<0.001	<0.01	<0.001
Carrot								
Carrot hard	50.4 ± 0.5	0.35 ± 0.00	38 ± 5	35 ± 5	64 ± 9	35 ± 5	146.9 ± 19.6	90.2 ± 1.3
Carrot soft	50.4 ± 0.5	0.35 ± 0.00	43 ± 6	30 ± 4	15 ± 2	26 ± 3	16.5 ± 4.1	93.2 ± 1.2
Carrot hard + sauce	60.6 ± 0.6	0.79 ± 0.01	43 ± 6	38 ± 5	66 ± 9	32 ± 4		
Carrot soft + sauce	60.7 ± 1.4	0.78 ± 0.02	52 ± 7	41 ± 6	15 ± 4	24 ± 3		
P	<0.001		0.001	0.001	<0.001	0.06	<0.001	<0.01
Composite								
Penne hard + carrot hard + sauce	108.0 ± 0.8	1.38 ± 0.01	42 ± 6	40 ± 5	64 ± 9	54 ± 7		
Penne hard + carrot soft + sauce	108.0 ± 0.8	1.38 ± 0.01	58 ± 8	43 ± 6	27 ± 4	46 ± 6		
Penne soft + carrot hard + sauce	123.0 ± 0.9	1.21 ± 0.01	47 ± 6	37 ± 5	55 ± 7	44 ± 6		
Penne soft + carrot soft + sauce	123.0 ± 1.0	1.21 ± 0.01	54 ± 7	39 ± 5	20 ± 3	41 ± 6		
P	<0.001		<0.001	0.08	<0.001	0.001		

or soft). To obtain similar visual volume of the samples, the same number of penne units and carrot units were used. The samples contained 16 ± 0.5 units (mean ± SD; six replicates) of penne (Albert Heijn private label) or 27 ± 0.8 units (mean ± SD; six replicates) of carrots (Albert Heijn private label), with and without 10 g (16–21% of sample weight) tomato sauce with basil (Grand Italia). The composite dishes were combinations of the samples with sauce and participants were required to consume the full amount served for each of the twelve samples. Through pilot testing, it was determined that these quantities were large enough to allow for several bites, but small enough to avoid satiation and allow for multiple sample presentations within each test session.

The penne hardness was varied by boiling for seven (hard) or twenty minutes (soft). The carrots were sliced in cubes of 12.5 × 12.5 × 12.5 mm, leading to 1.7 ± 0.3 cm^3 cubes (mean ± SD; five replicates). Carrot hardness was varied by boiling for two (hard) or twenty (soft) minutes. The samples were prepared thirty minutes before serving and kept warm using a bain marie before being served in 250 mL round cardboard cups with a metal fork. Participants received four samples per session with the order of sample presentation randomized within blocks. Participants never received more than two composite dishes in a single session to reduce the risk that participant satiation could influence their oral processing behaviour. The total energy served per study session ranged between 286 and 471 kcal.

Sample weight was measured before serving and sensory properties were rated by the participants after consumption. Participants rated the *liking, flavour intensity, hardness*, and *chewiness* of each sample on a 100-mm VAS scale ranging from 'not at all' (0) to 'extremely' (100) with anchors at the beginning and end of the line. Ratings were collected using Qualtrics survey software (version September 2021, Qualtrics, Provo, UT). The average weights of the 648 samples severed and their sensory evaluation can be found in Table 1.

The hardness (maximum force of first compression) of the penne and carrot was assessed using a double compression test over five replicates with the Texture Analyser (TA.XT Plus, Stable Micro Systems). A cell load of 5 kg and 50 kg was used for the penne and carrots, respectively. A constant test speed of 5 mm/s and strain up to 75% was used. The water content of the penne and carrot were measured five times by drying single units (1.8 – 3.2 g) for 18 h at 100 °C. The weight of the units were measured before and after drying. To assess the degree of moisture in penne and carrot, the moisture content based on a wet weight basis was calculated using $MC = (m_0 - m_1)/m_0$, where m_0 is the weight before drying and m_1 is the weight after drying.

2.4. Procedure

Participants came on three separate days (with at least two days in between) during lunch time to the laboratory. Participants were instructed to refrain from eating and drinking (except water) after 10PM the day before the test session and to avoid intensive exercise. In the mornings of all test sessions, participants were instructed to have the same breakfast and morning snack around the same time and were not allowed to eat or drink for the two hours prior the test session, in an effort to equilibrate appetite need state before each test session. Earlier food consumption from the morning was recorded at the beginning of each test session. Five participants did not fully adhere to these instructions, but were included in the data set when further analysis revealed excluding them did not lead to changes in the final results. After recording their food intake in the morning, participants rated their appetite feelings hunger, fullness, thirst, and desire to eat. Participants then received samples in a randomised order and were instructed to consume the full portion of each dish. Participants never received more than two composite dishes in a single session to reduce the risk that participant satiation could influence their oral processing behaviour. Participants were instructed to eat in their normal way, and to consume the full portion without taking breaks or sips of water. Following the last bite of each sample, participants rated their appetite and the sensory and hedonic characteristics of the sample. A mandatory two minute inter-sample interval was imposed between each sample, during which participants were instructed to take a sip of water to clean their palate. The consumption, sensory ratings, and appetite ratings were repeated until all four samples were consumed and rated. The appetite ratings for each sample and across a session can be found in the Supplementary Material Table 1 and 2.

2.5. Oral processing behaviour

Participants were video recorded during each test session using a webcam (Logitech C310 - HD Webcam) positioned at face level. Participants were instructed to look to the webcam during consumption of the samples and to minimise head movements. Videos were recorded continuously throughout the session and participants could not see themselves when they were recorded. Oral processing characteristics were annotated manually by trained video coders using a coding scheme developed previously (Forde et al., 2013a) using the software ELAN version 6.2 (Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen, The Netherlands). The coding scheme included point events (number of bites, number of chews) and continuous events (eating duration per bite, and cumulative total sample consumption time across bites). Two experimenters coded 84 samples (13% of all samples) independently. The agreement was 92% for the number of bites, 89% for the number of chews, 93% for bite duration, and 96% for total sample consumption time. This is an acceptable level of agreement (≥80 %) and in line with previously published recommendations (Haidet et al., 2009). The remaining videos were coded and data collated to derive summary measures of oral processing for each sample. The ER (g/min) was calculated by dividing the total sample weight by the total eating duration of the sample. The average bite size (g) was calculated by dividing the weight of the sample by the total number of bites of the sample; the number of chews per gram (chews/g) was calculated 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) by dividing the summation of the bite size durations by the weight of the samples; the chewing frequency (chews/g) by the number of chews by the OSE time; and the number of units per bite was calculated by dividing the average number of units of the samples by the number of bites.

2.6. Statistical analysis

The effects of penne hardness and sauce addition on oral processing behaviour were analysed with a repeated-measures linear mixed model with penne hardness, sauce addition, and penne hardness × sauce addition as fixed effect, participant and serving order as random effect, and liking as covariate. The same analysis was used for the carrot hardness and sauce addition, and penne hardness and carrot hardness in the composite dishes. Pearson's correlations with participants as covariate (Christensen, 2002; Shan et al., 2020) were used to determine relationships between ER and the oral processing characteristics, hedonic ratings, and sensory ratings. R version 4.1.2 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria) and the packages stats, emmeans, lme4, and lmerTest (Kuznetsova et al., 2017) were used to perform all statistical tests. P values of < 0.05 were be considered as statistically different.

2.7. Prediction equation

The fitting of two equations predicting the ER of the composite dishes were evaluated to investigate if ER of a dish is determined by the component with the lowest ER (limiting equation, Equation 1) or if there is an additive effect of the ERs of all dish components (additive equation, Equation 2). With the limiting equation (Eq 1) the predicted dish eating

Table 2
Oral processing behaviour of the samples. Values are means ± SEM. P values are presented for the effect of hardness, sauce addition, and the interaction of hardness and sauce (hardness × sauce).

Sample	Eating rate (g/min)	Bite size (g)	Number of chews (chews/g)	Chews per bite (-)	OSE time (s/g)	Chewing frequency (chews/s)	Units per bite (-)
Penne							
Penne hard	23.1 ± 1.1	6.1 ± 0.2	4.0 ± 1.5	23 ± 1	2.6 ± 0.1	1.5 ± 0.0	2.6 ± 0.1
Penne soft	32.9 ± 1.7	7.6 ± 0.3	2.8 ± 1.2	21 ± 1	1.8 ± 0.1	1.5 ± 0.0	2.3 ± 0.1
Penne hard + sauce	30.6 ± 1.6	6.4 ± 0.2	2.8 ± 1.2	17 ± 1	1.9 ± 0.1	1.5 ± 0.0	2.1 ± 0.1
Penne soft + sauce	39.9 ± 1.8	8.2 ± 0.3	2.1 ± 0.9	17 ± 1	1.4 ± 0.1	1.5 ± 0.0	2.1 ± 0.1
$P_{hardness}$	<0.001	<0.001	<0.001	0.08	<0.001	0.31	<0.001
P_{sauce}	<0.001	0.03	<0.001	<0.001	<0.001	0.64	<0.001
$P_{hardness\ x\ sauce}$	0.71	0.52	0.02	0.50	<0.01	0.14	0.06
Carrot							
Carrot hard	17.8 ± 0.8	4.8 ± 0.2	5.8 ± 2.4	27 ± 2	3.4 ± 0.2	1.7 ± 0.0	2.6 ± 0.1
Carrot soft	34.6 ± 1.7	5.8 ± 0.3	2.7 ± 1.3	16 ± 1	1.7 ± 0.1	1.6 ± 0.0	3.1 ± 0.1
Carrot hard + sauce	25.1 ± 1.1	6.7 ± 0.3	3.9 ± 1.5	26 ± 2	2.4 ± 0.1	1.6 ± 0.0	3.0 ± 0.1
Carrot soft + sauce	43.0 ± 1.9	7.0 ± 0.3	1.9 ± 0.8	13 ± 1	1.2 ± 0.1	1.6 ± 0.0	3.1 ± 0.1
$P_{hardness}$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P_{sauce}	<0.001	<0.001	<0.001	0.39	<0.001	0.06	<0.001
$P_{hardness\ x\ sauce}$	0.66	0.04	<0.001	0.52	<0.001	0.54	0.01
Composite							
Penne hard + carrot hard + sauce	31.3 ± 1.5	7.3 ± 0.3	3.0 ± 1.2	21 ± 1	1.8 ± 0.1	1.7 ± 0.0	2.9 ± 0.1
Penne hard + carrot soft + sauce	40.6 ± 1.8	7.4 ± 0.3	1.9 ± 0.7	14 ± 1	1.3 ± 0.1	1.5 ± 0.0	2.9 ± 0.1
Penne soft + carrot hard + sauce	33.9 ± 1.5	7.9 ± 0.3	2.6 ± 1.1	20 ± 1	1.6 ± 0.1	1.6 ± 0.0	2.8 ± 0.1
Penne soft + carrot hard + sauce	45.4 ± 2.0	8.1 ± 0.3	1.8 ± 0.7	14 ± 1	1.2 ± 0.1	1.5 ± 0.0	2.8 ± 0.1
$P_{hardness\ penne}$	0.03	0.01	<0.001	0.30	<0.001	0.20	0.28
$P_{hardness\ carrot}$	<0.001	0.27	<0.001	<0.001	<0.001	<0.001	0.29
$P_{hardness\ penne\ x\ hardness\ carrot}$	0.15	0.93	0.05	0.31	0.39	0.04	0.91

rate is obtained by taking the minimum eating rate of the components. With the additive equation (Eq 2) the predicted dish eating rate is obtained by the addition of the eating rate fractions of the components. In the equations *pER* is the predicted ER of the dish, *ER* the measured ER of each dish component, *w* the weight fraction, x the interaction coefficient, and *i* the dish component. Before the fit of the prediction equations were evaluated, outliers of the composite dishes were removed with the interquartile range method for each composite dish separately. In total twelve datapoints were removed. To see how well the equations predict the measured ERs of the dishes, the observed versus the predicted ERs were plotted, residual plots were made, and the mean absolute error (MAE), residual sum of squares (rSS), root mean square error (RMSE), and Akaike's information criterion (AIC) were calculated using Microsoft 365 Excel (Microsoft Corporation). The lower the MAE, rSS, RMSE, and AIC, the better the equation predicts the measured ER of composite dishes (Consonni et al., 2010).

(Eq 1) ***Limiting Equation***

$$pER_{limiting} = \text{minimum}(ER_i) = \text{minimum}(ER_{penne+sauce}; ER_{carrots+sauce})$$

(Eq 2) ***Additive Equation***

$$pER_{additive} = \sum (w_i * ER_i) = (w_{penne+sauce} * ER_{penne+sauce}) + (w_{carrots+sauce} * ER_{carrots+sauce})$$

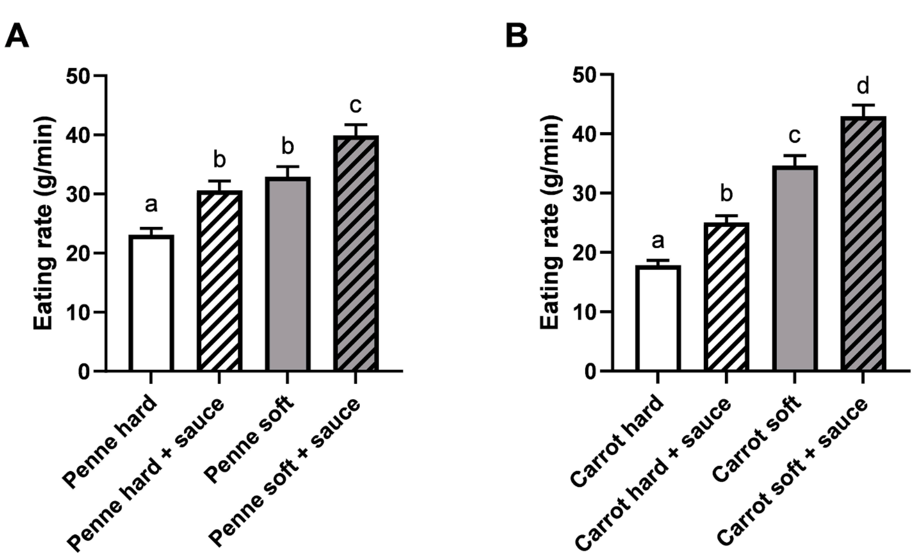

Fig. 1. Eating rate penne (A) and carrot (B) differing in hardness and with and without sauce. Error bars represent the standard error of the mean (SEM). Different lower case letters indicate significant differences between the means (P < 0.05).

3. Results

3.1. Eating rate and oral processing behaviour of single components

The dishes with soft penne and soft carrot were consumed with a significantly higher ER than the harder penne ($P < 0.001$) and harder carrot ($P < 0.001$) (Fig. 1). For the samples without sauce, soft penne was consumed with a 42% higher ER than hard penne and soft carrots were consumed 94% faster compared to hard carrots. For samples with sauce, soft penne was consumed with a 36% higher ER than hard penne and soft carrots was consumed with a 81% higher ER than hard carrots. The softer variants of the penne and carrot were consumed with larger bite sizes, lower number of chews per gram, and lower OSE time compared to their harder variants. Soft carrots were consumed with a lower number of chews per bite and chewing frequency compared to hard carrots, while this was not the case for the penne (Table 2).

Sauce addition significantly increased the ER of penne by 26% ($P < 0.001$) and carrot by 30% ($P < 0.001$) (Fig. 1). Sauce addition increased the bite size, decreased the number of chews per gram, and decreased the OSE time of the penne and carrot samples. Only for penne the addition of sauce decreased the chews per bite (Table 2). There was no interaction effect in ER between hardness and sauce for both the penne ($P = 0.71$) and carrot ($P = 0.66$).

3.2. Eating rate and oral processing behaviour of composite components

The composite dishes with soft penne were consumed with a 10% higher ER compared to the composite dishes with hard penne ($P = 0.03$) (Fig. 2). The composite dishes with soft carrots were consumed with a 32% higher ER compared to the composite dishes with hard carrots ($P < 0.001$). The composite dish with soft penne and soft carrot was consumed 45% faster than the dish with hard components. There was no interaction between penne hardness and carrot hardness ($P = 0.15$).

Both dishes with soft penne and dishes with soft carrots were consumed with a decreased number of chews per gram and OSE time compared to dishes with their harder variant (Fig. 2). However, dishes with soft penne were consumed with larger bite sizes than dishes with hard penne, while this was not the case for carrot. Conversely, dishes with soft carrot were consumed with significantly less chews per bite and lower chewing frequency than dishes with hard carrot, while this was not the case for penne (Table 2).

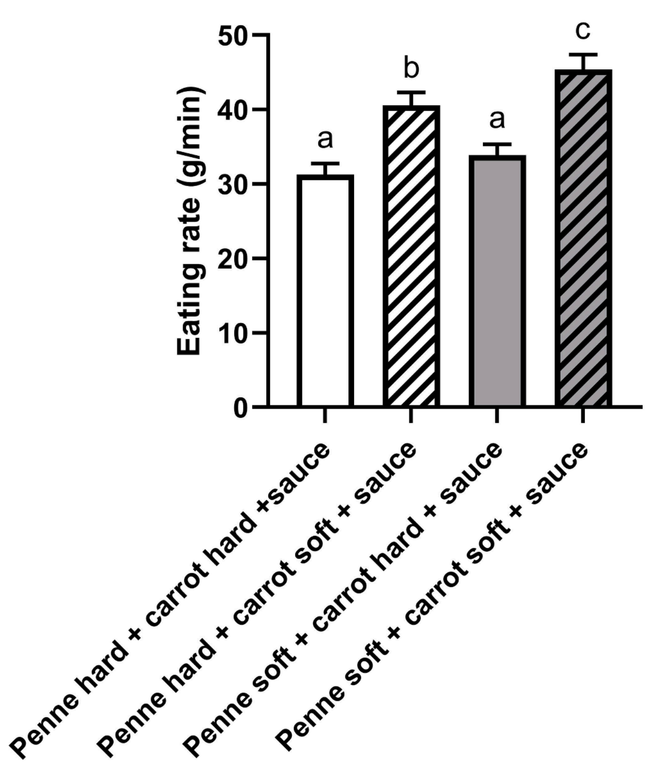

Fig. 2. Eating rate of the composite dishes. Error bars represent the standard error of the mean (SEM). Different lower case letters indicate significant differences between the means ($P < 0.05$).

3.3. Correlations with eating rate

In general, correlations with eating rate were higher for the oral processing behaviours than for the sensory and hedonic ratings. ER was negatively correlated with the number of chews per gram, number of chews per bite, and OSE time (Table 3). In addition, the ER was positively correlated with bite size. Chewing frequency (chews/sec) was not significantly correlated with the ER. The correlations between ER and perceived hardness were $r = -0.18$ ($p < 0.01$) for penne, $r = -0.54$ ($P < 0.001$) for carrot, and $r = -0.33$ ($P < 0.001$) for the composite dishes. The correlations between ER and the other sensory ratings or liking were weak ($r < 0.30$, see Supplementary Material Table 3).

3.4. Predicting the eating rate of a dish

The measured versus the predicted eating rates of the composite dishes are plotted in Fig. 3. The mean absolute error (MAE) of the limiting equation was 1.6 times larger than the MAE of the additive model (Table 4). The mean error was 25% for the limiting model and 15% for the additive model. The additive equation also had lower rSS, RMSE, and AIC than the limiting equation and thus had less error in predicting the ER of the dishes from the ER of the single components. For the additive equation, the average predicted eating rates of the four dishes were closer to the average measured eating rates compared to the limiting equation.

4. Discussion

This study demonstrated that modifying the hardness of several components had an additive effect on ER, rather than the ER of a dish being driven solely by its slowest component. The additive equation provided a better prediction of the eating rate of the dishes based on the eating rate of its components. Lower hardness of components increased the ER, both when served individually and within a dish. The addition of sauce increased ER around 30% for all single components.

When combining penne and carrot, the eating rate was best predicted by the addition of the individual eating rates of single components. This provides valuable insights when considering texture based approaches to modify meal eating rate and energy intake. Many previous studies have explore the impact of texture modification for a single food (Aguayo-Mendoza et al., 2019; Cahayadi et al., 2020; de Lavergne et al., 2015; Doyennette et al., 2019; Foster et al., 2006; Koç et al., 2014; Lasschuijt et al., 2017; Zijlstra, 2010), rather than the complex interplay between multiple textures within a meal, and the nett impact of these interactions have on eating rate. In studies with composite foods, the carrier food is typically the hardest/toughest food and has a

Table 3
Pearson's correlation coefficients between overall eating rate (g/min) and oral processing characteristics of the penne samples, carrot samples, and composite dishes. *P < 0.05, **P < 0.01, ***P < 0.001.

	Penne	Carrot	Composite
Bite size (g/bite)	0.40***	0.33***	0.14*
Number of chews (chews/g)	−0.82***	−0.78***	−0.75***
Chews per bite (-)	−0.59***	−0.63***	−0.61***
OSE time (s/g)	−0.85***	−0.80***	−0.79***
Chewing frequency (chews/s)	−0.02	−0.09	0.01
Units per bite (-)	0.12	0.27***	0.11

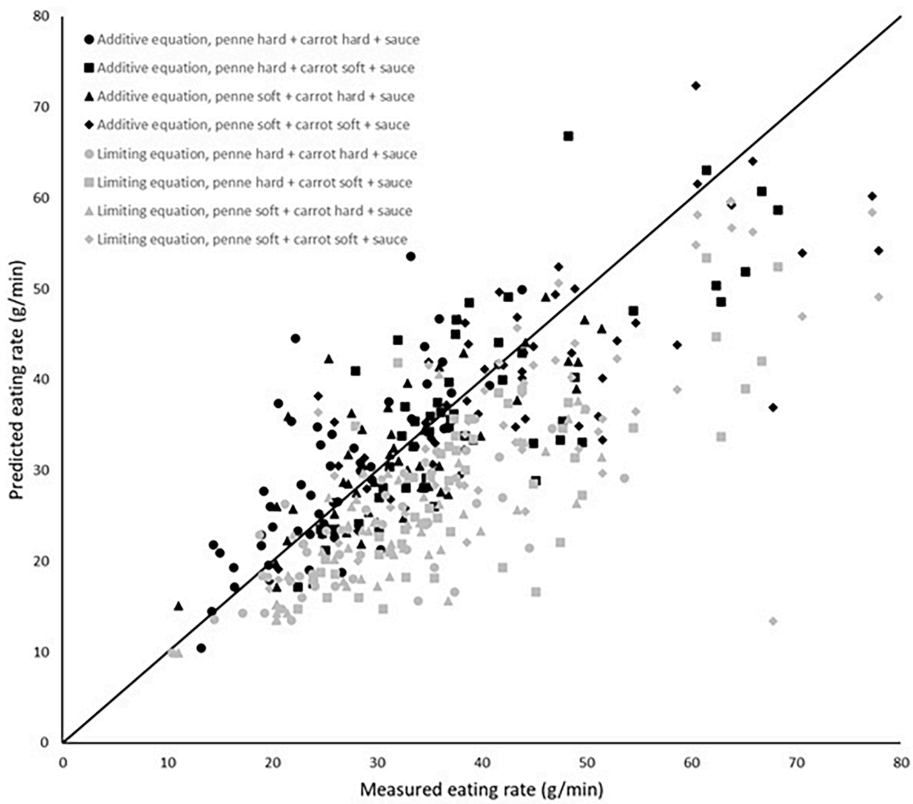

Fig. 3. Plot of the measured versus the predicted eating rates of the composite dishes (n = 204) by the limiting (grey) and additive (black) equations. The solid black line indicates a similar predicted and measured eating rate. The shape of the points indicate the different composite dishes with a circle for the hard penne with hard carrot and sauce, a square for hard penne with soft carrot and sauce, a triangle for soft penne with hard carrot and sauce, and a diamond for soft penne with soft carrot and sauce.

Table 4
Measured eating rates (g/min), predicted eating rates (g/min), mean absolute error (MAE), residual sum of squares (rSS), root mean square error (RMSE), and Akaike's information criterion (AIC) of the limited and additive equations.

	Measured	Limiting equation	Additive equation
Measured and predicted eating rates of dishes (g/min)			
Penne hard + carrot hard + sauce (n = 50)	29.9 ± 9.4	23.0 ± 6.5	26.3 ± 7.5
Penne hard + carrot soft + sauce (n = 50)	32.2 ± 8.9	23.8 ± 6.7	31.8 ± 8.4
Penne soft + carrot hard + sauce (n = 52)	39.5 ± 11.6	28.7 ± 9.4	36.9 ± 11.3
Penne soft + carrot hard + sauce (n = 52)	44.5 ± 13.9	35.9 ± 11.3	40.9 ± 11.5
MAE (g/min)		9.3	5.7
rSS		$28.0*10^3$	$12.0*10^3$
RMSE		11.7	7.7
AIC		1006	833

dominant effect on the rate of consumption (Bolhuis & Forde, 2020; van Eck, Wijne, et al., 2019). The current study showed that component textures combined cumulatively determine the overall ER of the dish, rather than ER being determined by a single limiting component. So, the texture of all components of meals should be modified to effectively decrease meal ER and thereby their intake.

Hardness showed to significantly affect oral processing characteristics and ER even when corrected for liking. The composite pasta dish with only soft ingredients was consumed 45% faster than the dish with only hard components. The soft dish was eaten with larger bite sizes and less chews than the hard dish. In the present study hardness modification had a larger effect on ER for the carrots than for the penne. This difference in effect size is due to the larger difference in hardness for carrots, though the penne and carrot cannot directly be compared directly due to their differences in composition, shape, surface area, and other texture attributes. Smaller food texture manipulations tend to have a weaker impact on oral processing behaviours and ER (Bolhuis & Forde, 2020) and too small hardness modifications may cause a lack of effect (Zijlstra et al., 2010). Previous studies which showed that softer foods increase ER of single food components (Aguayo-Mendoza et al., 2021; de Lavergne et al., 2015; Doyennette et al., 2019; Forde et al., 2017; Forde et al., 2013a; Foster et al., 2006; Koç et al., 2014; Lasschuijt et al., 2017; van den Boer et al., 2017) and meals (Bolhuis et al., 2014; Ferriday et al., 2016; Forde et al., 2013b; Langlet et al., 2018; Teo et al., 2022). For example, a lunch with hard hamburgers and rice salad was consumed 32% slower than a meal with their soft variants (Bolhuis et al., 2014) and multiple meals with whole components were consumed slower than their mashed variants (Forde et al., 2013b; Labouré et al., 2002; Langlet et al., 2018). A recent study which investigated the effect of combinations of food textures on *ad libitum* intake observed a higher 35% eating rate and 26% higher energy intake of the softer textured multicomponent meals compared to the harder meals (Teo et al., 2022). Harder foods require more effort and time be fractured into smaller particle sizes to facilitate sufficient particle softening, structure breakdown, and bolus lubrication (Hutchings & Lillford, 1988; Jalabert-Malbos et al., 2007). To facilitate this, harder foods tend to be consumed with smaller average bite sizes, longer OSE, and increased number of chews per bite. When combined this results in reductions of eating rate of 15–20% (g/min) and can lead to a 9–21% reduction in *ad libitum* energy intake (Bolhuis & Forde, 2020). It is suggested that a change of minimally 20% in ER of a meal by hardness modifications is relevant (Bolhuis & Forde, 2020; Forde, 2018). Although *ad libitum* intake was not measured in the current study, the differences in eating rate reported for the composite meals (Fig. 2) are within this range, and are expected to produce a significant reduction in ER and energy intake within a meal.

Similar to previous research (van Eck & Stieger, 2020), condiment addition increased the ER of a carrier food. In this study the magnitude of effect was similar for soft and hard penne and carrots. The addition of sauce decreased the number of chews per bite and decreased the ER.

This might be explained by increased softening of food particles due to sauce addition, leading to a more rapid agglomeration of the bolus to swallow. In foods with a high moisture content such as carrots, saliva and condiments adhere foods broken down into bolus pieces to form a cohesive bolus and thereby speed up the consumption. In low moisture foods, saliva and condiments migrate into the food where it moistens and softens, helping to form a compact bolus and thereby increase the ER (van Eck et al., 2020; van Eck & Stieger, 2020). Previous research showed that the addition of mayonnaise to bread (Mosca et al., 2022; van Eck et al., 2020; van Eck, Hardeman, et al., 2019), rice crackers (Janani et al., 2022), potato (van Eck et al., 2020), and carrots (Janani et al., 2022; van Eck, Wijne, et al., 2019) increase the ER by decreasing the number of chewing cycles. Research performed on the effect of the addition of sauce on oral processing behaviour and ER focussed on samples of one bite with a fixed size. The current study showed that the addition of sauce not only increased the eating rate by increasing the bite size and decreasing the number of chews.

Oral processing is a complex behaviour that is affected by many factors, within which consumers can adapt their oral processing behaviours in response to the geometric, texture and lubricant properties of the food being consumed. Knowing that all components of a meal contribute to their combined eating rate, makes it possible to model the impact of texture combinations on eating rate of more complex foods and meals than previously studied. The eating rate of an individual is a consistent behaviour that is a predictor of their *ad libitum* intake over time (McCrickerd & Forde, 2017). As such, an understanding of which textures can be combined to effectively achieve significant changes in eating rate of complex foods may have a longer-term impact on meal size and energy intake. Further research is needed to investigate whether the additive equation is generalizable to a wider range of meals with differ textures and whether this additive equation is applicable for predicting differences in energy intake. This knowledge creates new possibilities for meal design where the impact of texture can be modelled and combined to maximise eating pleasure and minimize intake. Similarly, being able to predict the eating behaviours associated with specific texture combinations makes it possible to give advice about which meal textures can applied to successfully increase or decrease ER and energy intake or stimulate energy intake in vulnerable populations.

Limitations of this study included differences in sample weight and energy. The weight of samples without sauce, samples with sauce, and composite dishes were different to be able to predict the eating rate of a composite dish from its components. However, eating rate decreases over consumption and portion size can influence oral processing behaviour (Almiron-Roig et al., 2015). Another limitation was that because of the study aims, the study design was not suitable to investigate energy intake (rate) due to amongst others energy density differences in the samples. Changing the cooking time of penne, leads to differences in water absorption and energy density. It remains unknown how much the hardness of the penne would influence the total energy consumed of a meal. It should be noticed that textural manipulations to stimulate or reduce food intake often lead to differences in energy density which is known to strongly affect the total amount of energy consumed (Rolls, 2009).

Modifying the hardness of multiple components in a dish had an additive effect on ER, where the ER of components cumulatively determined the ER of the composite dish, rather than the ER of a dish being driven by only the slowest (limiting) component. Decreased penne and carrot hardness increased ER, where the changes in ER and oral processing characteristics were larger with larger hardness differences. Sauce addition increased ER as well. This research suggests that it is possible to predict the overall ER of a dish from the ER of its single components. More research is needed to validate this in other composite foods, dishes or meals. These insights can be used to compose meals or to design heterogenous foods to influence ER that can be used to stimulate or moderate overall energy intake.

Conflict 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.

CRediT authorship contribution statement

Lise A.J. Heuven: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Kees de Graaf:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Ciarán G. Forde:** Funding acquisition, Supervision, Writing – review & editing. **Dieuwerke P. Bolhuis:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2023.104883.

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