Physiology & Behavior 238 (2021) 113495

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Impact of Individual Differences in Eating Rate on Oral Processing, Bolus Properties and Post-Meal Glucose Responses

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ARTICLE INFO

Keywords:
Eating rate
Food texture
Eating behaviour
Glycaemic Response

ABSTRACT

Purpose: Modifying food texture has been shown to influence oral processing behaviour. We explored the impact of food texture on oral processing, bolus formation and post-prandial glucose responses (PPG) among fast and slow eaters.

Methods: Male participants (N=39) were split into fast or slow eaters based on natural differences in eating rate when consuming two carbohydrate-equivalent test-meals differing in texture (white rice and rice cake). PPG and satiety responses were compared for fast and slow eaters over 120-min for each test-meal. Each groups test-meal PPG was compared for bolus and saliva properties at the point of swallow.

Results: White rice displayed lower instrumental hardness, chewiness and Young's modulus and was perceived less chewy, springy and sticky than rice cake. Slow eaters (n=24, white rice: 13.3 g/min; rice cake: 15.1 g/min) required an average 42% more chews per bite ($p < 0.001$), had 60% longer oral exposure time (OET), and consumed both test-meals ($p < 0.001$) at half the eating rate of fast eaters (n=15). Slow eaters had higher PPG following the rice cake meal at 15 ($p = 0.046$) and 45 min ($p = 0.034$) than fast eaters. A longer OET was a positive predictor of early PPG at 30-min after the white rice meal ($\beta = 0.178$, $p = 0.041$) and saliva uptake was a significant predictor ($\beta = 0.458$, $p = 0.045$) of PPG for slow eaters when consuming rice cake. Increasing food hardness and stiffness (Young's modulus) had a greater impact on eating rate for slow eaters than fast eaters.

Conclusions: Eating rate, oral exposure time and bolus saliva uptake were the predictors of an individual's post-prandial glycaemic response amongst slow eaters. Increasing the number of chews per bite with a longer oral exposure time increased saliva uptake in the bolus at the moment of swallowing and enhanced temporal changes in PPG, leading to greater glycaemic peaks in rice cake meal. Differences in eating rate between slow and fast

Clinical Trial registry: NCT04683432

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https://doi.org/10.1016/j.physbeh.2021.113495
Received 5 March 2021; Received in revised form 3 June 2021; Accepted 4 June 2021
Available online 9 June 2021
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eaters when consuming rice cake meal influenced temporal changes in PPG but not total PPG, and bolus properties did not differ between eating rate groups.

1. Introduction

Individuals differ naturally in the way they eat, with some consuming foods fast while others eat at a slower pace [1]. The differences in the pace we eat, whether fast or slow, are generally stable over time at an individual level and tend to be the same for a specific food [2]. There are many possible reasons for such stable eating pace patterns, including genetics [3,4], energy requirements [5], or lifestyle habits and environmental factors [6,7]. Research has shown that a faster eating rate is associated with higher energy intake [8], and may also affect glycaemic and insulin responses and post-meal satiety [9]. Over time, these eating rate differences may influence body weight and have been associated with increased cardio-metabolic risk and poorer health outcomes [10-12]. Growing evidence from feeding trials and population based dietary surveys in children and adults consistently shows that fast eaters consume greater energy, have higher adiposity and tend to gain weight at a faster rate over time [13-16].

Differences in eating behaviours can impact bolus breakdown during mastication, which can influence digestive kinetics including the rate and extent of metabolic response to ingested nutrients. The post-prandial glucose (PPG) response to ingested carbohydrates begins within the first 10-15 minutes of meal consumption, as glucose release begins during the oral phase of digestion and continues until enzymatic activity is partially reduced by the low gastric pH [17]. Having sustained higher PPG or hyper-glycaemia is a risk factor for type-2 diabetes and those that are susceptible are recommended to avoid hyper-glycaemic peaks, and to keep blood-glucose concentrations within the normal range [18,19]. Fast eaters tend to have a lower PPG [20-22], although studies have failed to confirm this finding consistently [23,24]. Differences in oral processing behaviours and bolus properties at swallow are the result of both an individual's eating behaviour, and the texture properties of the food being consumed. The glycaemic response to a fixed-carbohydrate load is influenced by the particle size of the bolus fragments at point of swallowing [25] where an increase in masticatory cycles has the dual impact of increasing total bolus surface area and bolus saliva uptake [9]. The extent of mastication also determines degree of food particles breakdown, bolus formation and accessibility for salivary amylase to act on [26]. Previous findings show that food texture can influence mastication and bolus properties where harder and drier foods require more chewing and more saliva uptake [27-30]. Modifications of a foods texture therefore encourages a natural adjustment in oral processing behaviours which have been shown to slow eating rate and reduce energy intake [31-33].

Several studies to date have demonstrated that extended mastication can increase post-meal feelings of satiety for the same consumed calories [34-36]. It remains unclear whether texture based differences in oral processing behaviour have the same impact on bolus properties, saliva uptake, PPG and satiety among fast and slow eaters. The possibility that food texture modifications could be applied foods to consistently moderate an individual's oral processing behaviours [37] and subsequent PPG response to mitigate metabolic risk is appealing, but remains untested.

The current study sought to (1) compare whether the oral processing behaviours (OPB), bolus and saliva properties and PPG responses differ between slow and fast eaters and (2) establish which elements of oral processing, bolus and saliva properties are responsible for observed differences in PPG responses between slow and fast eaters. We also compared whether (3) oral processing behaviours of slow and fast eaters were influenced to the same extent by differences in meal texture.

2. Materials and methods

2.1. Experimental protocol

The study was a randomised cross-over, non-blinded feeding trial. All data was collected at the Clinical Nutrition Research Centre of the Yong Loo Lin School of Medicine in the National University of Singapore. All participants arrived overnight fasted and completed one screening and two test sessions, where test sessions were conducted at least 5 days apart. The screening session included measures of body composition and fasting blood glucose, saliva collection and intraoral volume capacity measure. Both test-meal sessions required participants to consume a fixed carbohydrate test meal and have their post-prandial glycaemic and satiety responses recorded for two hours. For all meal sessions, participants were instructed to eat in their normal, natural way and were given no instructions to follow a pre-defined eating protocol. Participants were classified as fast and slow eating rate groups post-hoc, based on the observed natural variations in their eating rate for two test meals.

2.2. Power Calculation

Previous research to explore the impact of oral processing on glycaemic responses applied a difference in iAUC glucose with an effect size (Cohen's d_{av}) of 1.24 when participants consumed foods with different particle sizes (small vs large) [38]. The current study recruited a minimum sample size of 15 per group to detect a difference in iAUC glucose between slow and fast eaters with an effect size of at least 1.1 with 80% power and 5% significance level. Participant recruitment was extended to account for an anticipated attrition rate of 30%.

2.3. Participants Characteristics

Male participants (N=40) of Chinese ethnicity aged 21 to 40 years old were recruited to participate in the current study. The video recording of one participant's test meal could not be retrieved, so data analysis was completed on data from N=39 participants. Recruitment was restricted to male subjects to reduce gender variability in oral processing behaviours and remove the contribution of hormonal variability in glycaemic responses. Participants of Chinese origin were recruited to reduce ethic variability in glucose metabolism previously observed across ethnicities in Singapore [39]. Participants were screened to meet inclusion criteria which included a Body Mass Index (BMI) between 18-25 kg/m^2, with a minimum body weight of 45 kg and blood pressure $\leq$ 140/90 mmHg and fasting blood glucose $\leq$6 mmol/L. Body composition measures included height and weight (SECA 763, Germany), Bio-electric impedance body composition analysis (Tanita Corp., BC-418, Tokyo, Japan), blood pressure (Omron HEM-907, Japan) and fasting blood glucose through finger prick method (Accu-check Safe-T-Pro Plus, Roche, Germany). All participants were screened to have a full set of natural teeth, no history of pain or discomfort in jaw movements or excessive teeth clenching or grinding and no caries, periodontal disease or no impaired salivation abilities. Participants were deemed ineligible if they had allergies or strong dislike of the test-meals, or were currently using any medication that may influence appetite or glucose metabolism. Eligible participants provided written consent and were financially compensated for their participation. Ethical approval of the study was obtained by the National Healthcare Group Domain Specific Review Board (NHG DSRB, Reference Number: 2018/01091), Singapore. The trial was registered at Clinical Trial registry: NCT04683432.

2.4. Saliva Collection

Unstimulated saliva flow rate was determined in all participants using the passive drooling technique [40]. Saliva was collected between 9 am to 11 am to avoid circadian variation. Stimulated saliva flow rate was measured where participants were instructed to chew a piece of parafilm (0.29g, Parafilm M PM996) like a piece of chewing gum, and allowing saliva to flow naturally into a pre-weighed vial. Unstimulated saliva was collected without the use of parafilm. Saliva was collected in duplicate and measured over a period of 5-minutes with a 2-minute interval in between each collection. Average α-amylase activity (U/ml) [27] was determined using a colorimetric assay (Salimetrics Assay #1-1902, Salimetrics, LLC.) and cell imaging reader (Cytation 5, Winooski, VT, USA).

2.5. Test Meals and Behavioural Coding analysis of Oral Processing Behaviours

Commercially available white rice (WR) and rice cake (RC) were selected as test meals based on previously observed differences in oral processing behaviour associated with their consumption [41,42]. Both test meals were chosen as familiar foods that were frequently consumed in Singapore. Test meals were matched to contain 50 g available carbohydrate for WR (106.3 g cooked weight; 222.0 kcal; Double FP Thai Hom Mali, Thailand) and RC (115.9 g cooked weight; 219.5 kcal; Sungji Topokki, Korea). Each test meal was served on test days separated by a minimum of 5 days. The WR was cooked in a 1:1 ratio with water in a rice cooker (Toyomi RC 515). The RC was prepared by boiling for 3 minutes and cooled and served in whole pieces at room temperature (22±2°C) in its original 10 g tubular-shaped form. Participants arrived at the test centre at 9am in a fasted state. Test meal was served on a plate with a fork and participants were asked to 'eat in their normal way' and to consume the full portion of each meal. Participants were video recorded during meal consumption using a webcam (Logitech HD c310) that was positioned at eye level to capture participant's meal consumption. Participants could not see themselves while being recorded. Filtered water (250 mL ±0.05) was provided after test meal completion.

Each participants video recording for their test meal were coded post-hoc by a trained coder to quantify their eating behaviours using a pre-defined coding scheme. This information was used to stratify participants into fast and slow eaters, based on the observed natural variations in oral processing behaviours across the two test meals. Quantitative information on each eating behaviour was derived using annotation software Elan (ELAN 5.8, Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen, The Netherlands) and a standardised behavioural coding approach described previously [2,42]. This coding scheme captured the frequencies of key 'point' events (bites, chews and swallows) and duration of a single 'continuous' event (time of food in mouth). Eating microstructure patterns were derived from the point and continuous events and comprised bite size (g/bite), eating rate (g/min), chews per bite (-) and oro-sensory exposure time (s) defined as the total time that food spent in-mouth during the meal. A minimum of 10% of the videos were blind-validated by a second coder through standard reliability measurements (≥ 80 % agreement) to be considered acceptable. Intra-class correlation coefficient showed high consistency between coders, ICC = 0.879– 0.999, with the 95% confidence interval ranging from 0.01 to 1.00 prior to data analysis.

2.6. Blood Glucose measurements

Blood glucose was measured using the finger prick method (Abbott, IL, USA). Blood samples were taken before meal at baseline, and post meal at 5, 10, 15, 30, 45, 60, 90 and 120 min. Blood glucose concentration at each time point was measured with a glucose dehydrogenase assay (HemoCue 201 RT, Sweden).

2.7. Appetite and Sensory Ratings for the Test Meals

Participants completed appetite ratings for *hunger, fullness, prospective intake* and *desire* to eat on a 100-point visual analogue scales (VAS), anchored from "Not at all <attribute>" (0) to "Extremely <attribute>' (100). Appetite ratings were presented in a randomised order. Appetite ratings were completed prior to the test-meal (Time 0 min) and at 15 minutes interval post meal (15, 30, 45, 60, 75, 90, 105 and 120 min). Test meals sensory properties (*firmness, chewiness, stickiness, springiness, sweetness, saltiness, pleasantness/liking*) were assessed after the first bite of the test meal. All scales were anchored from "Not at all" (0) to "Extremely" (100) and ratings were collected using CompuSense Cloud software (CompuSense Inc., Guelph, ON, Canada).

2.8. Texture Analysis

Instrumental texture measures were collected for both test foods using dual-compression textural profile analysis (TPA) [41]. TPA was carried using a TA•XT plus Stable Micro Systems Texture Analyser (Stable Microsystems Ltd, Surrey, England) equipped with a flat, circular compression plate (75 mm diameter, P/75). A spoonful of white rice (cylindrical shape; 45 Ø x 30mm) and a unit of rice cake (35 × 15 × 14mm) were used. TPA was performed at 22 ± 1 °C at a compression speed of 1 mm/s up to a strain of 30%. TPA analysis was performed with a minimum of eight replicates on each test food. The compression was carried with 5 seconds waiting time between the first and the second compression. Hardness (maximum force of 1st compression), adhesiveness (negative area after 1st compression), springiness (distance of height during second compression by the first compression distance), cohesiveness (Area under 2nd compression/area under 1st compression), chewiness (gumminess × springiness), resilience (area after maximum force of 1st compression/area before maximum force of 1st compression) and Young's modulus (slope of stress–strain curve during the first compression from 0 to 5% strain) were obtained.

2.9. Bolus Collection and Characterisation

Bolus collection for each food (WR: 5 ± 0.5 g and RC: 5.5 ± 0.5 g) was completed following the final blood draw and appetite rating. Participants were asked to chew and expectorate at the point of first swallow into a pre-weighed container. This was followed by rinsing with water (25 mL) to allow remaining food particles to be expectorated into the same container. Bolus measures were completed in duplicate. The weight of each bolus sample was recorded and derived using the following formula; Wet bolus (g) = [Weight of rinsing water (g) + wet bolus (g) + container (g)] – [weight of rinsing water (g) – weight of container (g)]. Bolus samples were processed with TRIS buffered saline at pH 10 to inactivate salivary amylase and stored at -20°C. Bolus particle analysis were carried out on defrosted samples at ambient temperature. Each bolus sample was separated in an individual 100 mm x 15 mm petri dish using a standardised protocol [43]. Thereafter, the bolus samples were dried in an oven (Memmert MEMMUF110) at 60°C for 3 hours, cooled for 1 hour before the petri dish was scanned individually and processed with Image-J, Fiji analysis [44] to derive number of particles (-),average particle size (mm^2), and total surface area (mm^2) in each bolus sample. The saliva uptake (%) and saliva incorporation rate (SIR) within each bolus were calculated to derive relative mass of saliva absorbed into the bolus at the moment of swallowing and the rate at which saliva was absorbed.

$$SalivaUptake(\%) = \frac{Weight\ of\ wet\ bolus\ (g) - Weight\ of\ food\ (g)}{Weight\ of\ food(g)} \times 100$$

$$SalivaIncorporationRate(g/min) = \frac{Weight\ of\ wet\ bolus\ (g) - Weight\ of\ food\ (g)}{Time\ taken\ in\ mouth\ (min)}$$

2.11. Statistical Data Analysis

The video recording of one participant's test meal could not be retrieved. Analysis was completed on complete data from 39 participants. Five participants were removed from bolus analysis due to incomplete bolus recovery with led to negative values. Saliva analysis and comparison of saliva uptake and SIR were completed on 34 participants. Data was checked for normality visually and statistically using quantile-quantile plot (Q-Q plot) and Shapiro-Wilk test prior to analysis and square-root transformed where appropriate. All data were presented as mean, standard deviation (SD) or standard error of means (SEM) as appropriate.

Agglomerative hierarchical cluster analysis (HCA) was performed to separate participants into clusters based on natural differences in their observed eating rate for both test meals. Squared Euclidean distance between pairs of participants or clusters with Ward's linkage was used to assist with the merging process in SPSS. Validation of two to four clusters was conducted in R using "silhouette" and "NbClust" function, to yield two clusters with higher average silhouette width [45]. The mean eating rate for both test foods was compared between the two clusters and confirmed that one group had a significantly slower eating rate compared to the other for both test foods, enabling the clusters to be categorised as slow and fast eaters. Independent t-tests were used to analyse differences in oral processing behaviours, bolus properties, saliva properties and appetite ratings between fast and slow eaters.

Incremental area under the curve (iAUC) was calculated for both glucose and appetite ratings using the trapezoid rule [46] from 0 to 120 min or at particular time segments of interest, ignoring the area beneath the baseline. Linear mixed model in SPSS was used to test for effect of grouping, time and their interaction on glucose concentration and appetite ratings separately while controlling for the baseline measurements. Grouping, time and their interaction were the fixed factors while the repeated subcommand was used to model the correlation in the repeated measures over time. Mean differences in glucose concentration at each time point between the two groups was compared using ANCOVA with baseline glucose concentration as the covariate. Finally, Partial Least Squares Regression (PLSR) was used to identify effect of oral processing variables (oral processing, bolus and saliva properties) that most influence blood glucose ($iAUC_{30}$, between 0 to 30 min) for the two test foods across the full cohort, and by eating rate group. Approximate t-tests of regression coefficients was based on jack-knife variance estimates. Summary plots were created using selected regression coefficients. PLSR was performed using "pls" package in R. A final variable selection was completed using a lasso regression alongside PLSR with the "glmnet" package in R, and was consistent with the most influential variables identified by PLSR (results not shown).

To compare whether a harder food texture had a larger effect on oral processing behaviours of fast or slow eaters, we disregarded the original HCA split of the 39 participants, and clustered them based on their eating rate for the softer test food (white rice). Participants were median-split into fast and slow eaters based on their observed eating rate for white rice. This enabled a comparison of the fast and slow groups regarding their eating rate of the harder test foods (rice cake), to observe which groups eating behaviour was most affected by the texture difference between test foods. The subsequent change in eating rate (g/min) was then compared for fast and slow eating groups for the harder test meal (RC). Independent t-tests were used to test for differences in eating rate between the two new groups separately for each type of food. All Statistical analyses were performed using SPSS (IBM SPSS statistics, version 26) and R statistical software (version 1.0.136; R-Studio Inc.), with alpha = 0.05. Data and figures were processed in Microsoft Excel spreadsheet (2010).

3. Results

Participant characteristics (N=39) are summarised in Table 1. All anthropometric measures were within normal range. Intraoral volume, stimulated saliva flow rate and stimulated amylase activity across both eating rate groups were in line with previously reported values [27,47]. Slow and fast eaters did not differ significantly across all baseline measures.

3.1. Sensory and Instrumental Texture Characteristics of the Test Meals

The sensory properties and instrumental texture measures for WR and RC are summarised in **Table 2**. There were no significant perceptual differences between slow and fast eaters on both test foods ($p > 0.05$). All participants rated RC as significantly higher in perceived *chewiness* and *springiness* ($p < 0.001$; data not shown) than WR, which was confirmed by TPA analysis. The RC was perceived significantly higher in *stickiness* ($p < 0.001$) than the WR which is in agreement with the significantly higher TPA adhesiveness ($p = 0.003$) of RC compared to WR.

3.2. Oral Processing, Bolus and Saliva Characteristics of Slow and Fast Eaters

Table 3 summarises the oral processing behaviours, bolus and saliva properties of slow and fast eaters for each test meal. Average bite size and chew rate (chews/s) did not differ significantly between the eating rate groups for WC and RC. Slow eaters took consistently more chews per bite for both test meals, with approximately two times more chews per bite for WR and 1.6 times more chews per bite for RC than fast eaters. Slow eaters had a 60% increased oral exposure time, and ate both test meals at approximately half the eating rate of fast eaters ($p < 0.001$). The eating rate of slow eaters was significantly ($p = 0.044$) higher for RC compared to WR. There was no significant difference in eating rate for both test meals amongst fast eaters ($p = 0.263$). RC was consumed with 1.8 g/min (12%) higher eating rate than WR by slow eaters. Similarly, RC was consumed with 2.2 g/min (9%) higher eating rate than WR by fast eaters.

Despite the observed differences in oral processing behaviour, the bolus and saliva properties for each test meal were not significantly different between slow and fast eaters ($p > 0.05$). Both eating rate groups had a significantly larger number of bolus particles of smaller particle size, larger total surface area and greater saliva uptake for WR compared to RC ($p < 0.001$). Comparison of the test foods shows the WR bolus at swallow had approximately three times the total surface area compared to RC, with similar differences between the test food boluses for both slow and fast eaters ($p < 0.001$) (**Table 3**). In this regard, bolus properties are different between test foods, but there were no differences between slow and fast eaters within each test food.

Table 1
Participant baseline characteristics of slow and fast eaters

Males (N=39)	Slow Eaters (n=24)	Fast Eaters (n=15)
Age (years)	26.0 (4.2)	27.3 (4.6)
Body mass index (kg/m^2)	21.3 (1.8)	21.2 (1.6)
Body fat (%)	15.3 (3.7)	13.7 (4.2)
Systolic blood pressure (mmHg)	119.5 (8.3)	117.6 (8.1)
Diastolic blood pressure (mmHg)	75.7 (6.2)	71.3 (7.3)
Fasting blood glucose (mmol/L)	4.6 (0.5)	4.8 (0.5)
Intraoral volume (mL)	73.2 (10.9)	73.9 (13.4)
Unstimulated saliva flow rate (g/min)	0.6 (0.4)	0.4 (0.2)
Stimulated saliva flow rate (g/min)	1.6 (0.7)	1.4 (0.6)
Unstimulated α-amylase activity (U/mL)	67.6 (48.1)	72.2 (60.7)
Stimulated α-amylase activity (U/mL)	106.0 (56.1)	99.9 (66.6)

Values are presented as Mean (±SD).

Table 2
Sensory properties of slow (n=24) and fast (n=15) eaters and TPA measures for White Rice (WR) and Rice Cake (RC)

	White Rice (WR)			Rice Cake (RC)		
Sensory Ratings	Slow	Fast	*p*	Slow	Fast	*p*
Firmness (mm)	69.5 (2.8)	65.2 (6.9)	0.514	59.7 (4.4)	66.0 (7.0)	0.429
Chewiness (mm)	48.5 (5.8)	44.3 (7.4)	0.659	85.4 (2.6)	87.6 (3.9)	0.627
Stickiness (mm)	42.1 (6.1)	38.5 (7.7)	0.716	77.6 (3.0)	84.9 (2.4)	0.090
Springiness (mm)	29.0 (4.7)	28.9 (6.7)	0.991	73.4 (4.0)	78.1 (4.1)	0.438
Sweetness (mm)	25.6 (4.4)	29.6 (5.0)	0.554	30.8 (5.1)	29.4 (6.9)	0.868
Saltiness (mm)	6.9 (2.0)	12.9 (4.1)	0.153	25.0 (4.9)	19.3 (5.1)	0.441
Pleasantness/ Liking (mm)	28.9 (4.1)	38.8 (6.1)	0.169	37.0 (4.3)	42.2 (6.1)	0.483
TPA Analysis	**White Rice (WR)**		**Rice Cake (RC)**		***p***	
Hardness (N)	2.84 (0.22)		6.78 (0.17)		**< 0.001**	
Adhesiveness (N*s) ^	0.06 (0.03)		1.95 (0.49)		**0.003**	
Springiness (-)	0.55 (0.16)		0.92 (0.01)		0.138	
Cohesiveness (-)	0.23 (0.02)		0.89 (0.00)		**0.001**	
Chewiness (-)	39 (15)		566 (13)		**< 0.001**	
Resilience (-)	0.14 (0.02)		0.57 (0.00)		**0.001**	
Young's Modulus (Pa)	515 (327)		2422 (128)		**0.017**	

Independent T-test, $p < 0.05$ (2-tailed). ^Values for adhesiveness were converted to absolute values. Data are presented as Mean (SEM). N: Newton; N*s: Newton-second; -: Dimensionless unit; Pa: Pascal.

Taken together, these findings confirm that the difference in food texture between WR and RC had a significant impact on oral processing behaviours and bolus properties observed among both slow and fast eaters. While oral processing behaviour differed significantly between slow and fast eaters for both test meals, bolus properties of both test foods were similar for slow and fast eaters. We therefore sought to compare whether differences in oral processing behaviour had an impact on post-prandial glucose responses (PPG).

3.3. Post-prandial glucose response during test meals of slow and fast eaters

Figure 1a indicates no significant interactions between temporal changes in glucose release between slow and fast eaters for the WR test meal ($p = 0.451$). Differences at each time point were not significantly different ($p > 0.05$) between the two eating rate groups, while controlling for baseline glucose.

The bar chart insert summarises blood glucose incremental area under the curve (iAUC) for slow and fast eaters during the early (0-30 min), later (30-120 min) and total (0-120 min) post-prandial period for the WR meal. iAUC did not differ significantly amongst slow and fast eaters for the early ($p = 0.154$), later ($p = 0.134$) and total ($p = 0.835$) post-prandial period.

Figure 1b summarises the PPG following consumption of RC and shows significant differences between fast and slow eating rate groups at 15 ($p = 0.046$) and 45 minutes ($p = 0.034$). There was no significant interaction between time and eating rate group ($p = 0.693$). PPG peaked at 30 min for both slow and fast eaters, which was earlier than for WR which peaked at 45 min. Similar to the WR, the bar chart insert indicated no significant difference in blood glucose iAUC for RC in the early (0-30 min; $p = 0.121$), later (30-120 min; $p = 0.390$) and total (0-120 min; $p = 0.067$) post-prandial period between slow and fast eaters. Differences in total iAUC (0-120 min) were trending towards significant with slow eaters having a higher PPG than fast eaters ($p = 0.067$).

3.4. Factors Affecting PPG of Slow and Fast Eaters in the Early Post-Prandial Period (iAUC 0-30 min)

The oral processing, bolus and saliva variables that influenced early PPG (***iAUC 0-30 min***) most were compared for slow and fast eaters (Fig. 2a-d). A longer oral exposure time and slower eating rate were consistently shown to be significant predictors of PPG in the first 30 minutes post-meal for both WR and RC in the slow eating rate group. In addition, saliva uptake into the bolus at the moment of swallowing was a significant predictor of PPG for RC among slow eaters ($\beta = 0.458$, $p = 0.045$). Eating rate was a negative predictor of PPG, for slow eaters (WR: $\beta = -0.157$, $p = 0.046$; RC: $\beta = -0.159$, $p = 0.035$) and only in RC for fast eaters ($\beta = -0.168$, $p = 0.008$), highlighting that faster eating rates were associated with lower PPG. Slow eating was associated with taking more chews per bite, and longer oral exposure time (WR: $\beta = 0.178$, $p = 0.041$; RC: $\beta = 0.160$, $p = 0.049$) and together were significant predictors of a higher PPG in the first 30 minutes for both test foods.

For fast eaters none of the oral processing or bolus variables predicted early PPG for WR. In line with slow eaters, among the fast eating group for RC there was a positive relationship between longer oral exposure time ($\beta = 0.189$, $p = 0.015$) and higher early PPG, and eating rate ($\beta = -0.168$, $p = 0.008$) was a negative predictor of PPG.

For exploratory purposes, group comparison between food indicated longer oral exposure time ($\beta = 0.170$, $p = 0.001$), more chews per gram ($\beta = 0.130$, $p = 0.002$) and slower eating rate ($\beta = -0.168$, $p < 0.001$) as predictors for RC, but not WR in the early PPG phase.

3.5. Eating Rate and Post-Meal Satiety

The total iAUC values of the satiety measures are summarised in

Table 3
Oral processing, bolus and saliva properties for slow (n=24) and fast (n=15) eaters for White Rice (WR) and Rice Cake (RC).

Oral Processing and Bolus Properties	White Rice (WR)			Rice Cake (RC)		
Oral processing behaviour	Slow	Fast	*p*	Slow	Fast	*p*
Bite size (g/bite)	6.3 (0.4)	6.1 (0.4)	0.767	10.1 (0.6)	11.4 (0.7)	0.137
Chew rate (chews/s)	1.3 (0.0)	1.2 (0.1)	0.327	1.4 (0.0)	1.3 (0.1)	0.208
Chews per bite (no.)	36.9 (2.8)	19.7 (1.8)	**<0.001**	57.7 (4.4)	35.6 (2.1)	**<0.001**
Chews per gram (no.)	6.1 (0.4)	3.3 (0.3)	**<0.001**	5.8 (0.3)	3.2 (0.2)	**<0.001**
Oral exposure time (s)	506.8 (26.2)	292.1 (18.9)	**<0.001**	488.1 (23.7)	289.4 (18.2)	**<0.001**
Eating rate (g/min)	13.3 (0.6)	23.2 (1.6)	**<0.001**	15.1 (0.47)	25.4 (1.6)	**<0.001**
Bolus and saliva properties						
Bolus particles (no.)	1152.4 (84.4)	1080.7 (120.5)	0.630	295.4 (36.7)	314.1 (49.8)	0.765
Total surface area (mm^2) (Post-mastication)	2318.5 (107.2)	2373.0 (212.1)	0.821	815.7 (70.9)	962.9 (149.4)	0.509
Particle size (mm^2)	2.1 (0.1)	2.4 (0.2)	0.320	3.5 (0.4)	3.4 (0.3)	0.864
Saliva uptake (%)^	56.7 (7.7)	60.1 (10.3)	0.795	47.9 (6.3)	45.0 (10.3)	0.811
Saliva incorporation rate (g/min)^	4.5 (0.6)	6.8 (1.2)	0.101	4.1 (0.4)	4.6 (0.8)	0.539

Independent T-test, $p < 0.05$ (2-tailed). ^ Slow eaters: n = 21; Fast eaters: n =13. Data are presented as Mean (SEM).

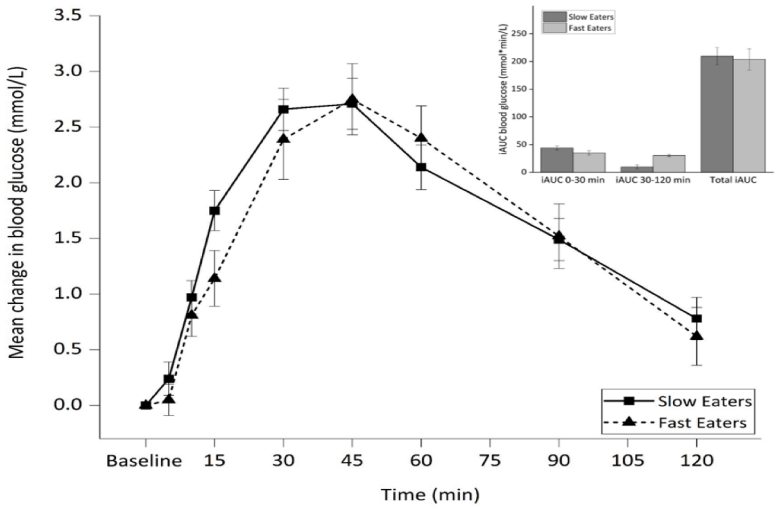


Fig 1a. Comparison of mean postprandial blood glucose concentration following White Rice (WR) consumption among slow (n = 24) and fast (n = 15) eaters. All error bars are standard errors. Insert shows the incremental area under the curve (iAUC) for glucose at 0-30 min, between 30-120 min and total iAUC (0-120 min).

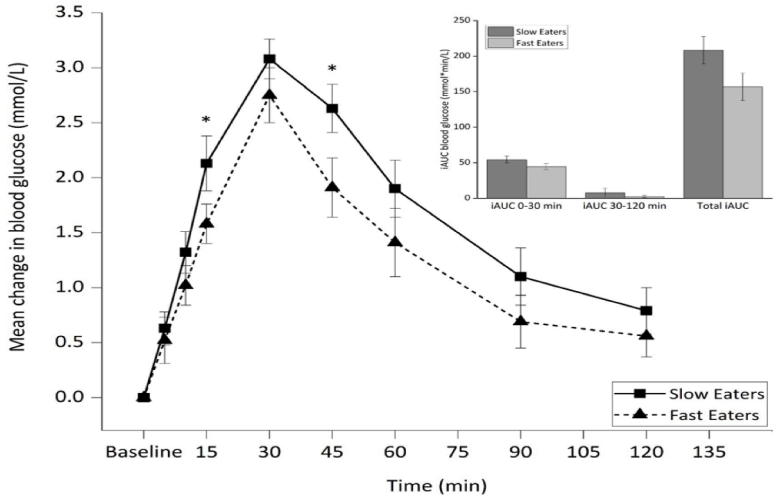


Fig 1b. Comparison of mean postprandial blood glucose concentration following Rice Cake (RC) consumption among slow (n = 24) and fast (n = 15) eaters. ANCOVA indicated significant differences between slow and fast eaters at 15 and 45 minutes ($p < 0.05$). All error bars are standard errors. Insert shows the incremental area under the curve (iAUC) for glucose at 0-30 min, between 30-120 min and total iAUC (0-120 min).

Table 4. There were no significant differences in post-meal satiety for all appetite ratings between the slow and fast eating rate groups for either test meal.

3.6. Comparison of the Impact of Food Texture on Eating Rate between Slow and Fast Eaters

The previous results highlight differences in oral processing behaviour between slow and fast eaters as they relate to PPG. The comparisons did not enable the understanding of whether one eating rate group's oral behaviour would be more affected in response to a modification of food texture. Results from the instrumental texture analysis (Table 2) displayed higher values for RC for hardness, adhesiveness, chewiness and Young's modulus (stiffness) than WR. For the sake of simplicity, we refer here to RC as "harder" food.

To compare whether a "harder" food texture (RC) had a larger effect on the oral processing behaviours of slow or fast eaters, all participants were re-grouped for a new categorisation (see section 2.11). Based on group-wide differences in eating rate for the "softer" test food (WR), participants were median-split into two even groups of slow (n=19, 21.9 g/min) and fast eaters (n=20, 12.1 g/min), indicating that fast eaters ate WR at almost twice the speed of slow eaters. The impact of serving a "harder" food texture on the eating rate of each group was compared and is shown in Figure 3. Slow eaters significantly increased their eating rate when consuming RC compared to WR ($p = 0.003$), such that the "harder" food texture of RC increased eating rate. Fast eaters did not differ in their eating rate between WR and RC ($p = 0.857$), despite taking more chews per gram for RC than for WR ($p = 0.058$; data not shown). Fast eaters therefore consumed both test meals at a consistently similar pace, regardless of the texture of the food.

4. Discussion

The current study demonstrated that natural variations in eating rate resulting from significant differences in oral processing behaviours impact early-PPG responses to a fixed carbohydrate meal. Slow eaters took more chews per bite, had a longer oral exposure time, and trended towards having a higher total PPG iAUC for rice cake (0-120 min) than fast eaters. Group wide regression revealed that the higher PPG for rice cake was driven by chews per gram, oral exposure time and eating rate,

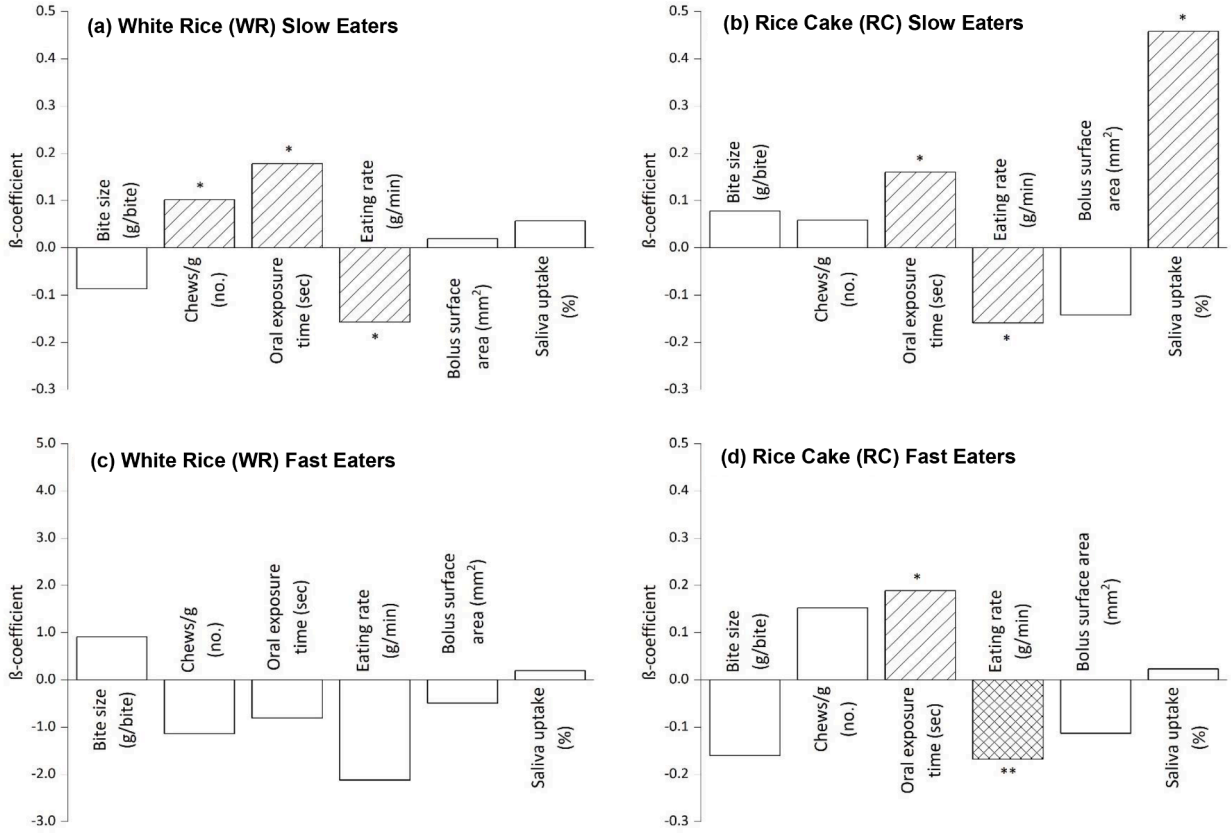


Fig 2a-d. Partial least square regression (PSLR) to investigate effects of oral processing, bolus and saliva variables for WR and RC on glucose $iAUC_{0\text{-}30min}$ among slow (n = 21) and fast eaters (n = 13). Positive β-coefficient values represent predictors associated with an increase in glucose $iAUC_{0\text{-}30min}$ while negative β-coefficient values represent predictors associated with a decrease in glucose $iAUC_{0\text{-}30min}$. *$p \leq 0.05$; **$p \leq 0.01$. Variables that were not significant and not shown include: Chew rate (chews/s), chews per bite (no.), particle size (mm^2), bolus particles (no.) and SIR (g/min).*

Table 4
Appetite ratings ($iAUC_{120}$) of White Rice (WR) and Rice Cake (RC) in slow (n=24) and fast (n=15) eaters.

	White Rice (WR)			Rice Cake (RC)		
$iAUC_{120}$*	Slow	Fast	*p*	Slow	Fast	*p*
Hunger	1264.4 (390.4)	1517.9 (456.9)	0.484	1312.1 (321.7)	929.3 (317.7)	0.563
Fullness	679.9 (217.7)	451.9 (215.9)	0.580	589.0 (169.1)	414.7 (258.9)	0.448
Prospective intake	1044.0 (377.2)	994.8 (300.8)	0.594	1467.2 (284.2)	836.2 (286.6)	0.162
Desire to eat	1357.6 (371.5)	1591.0 (473.6)	0.455	1470.4 (399.5)	1109.5 (341.1)	0.586

*Data was square root transformed prior to analysis. Data presented as untransformed means with standard deviations for ease of comparison. Independent T-test was performed (2-tailed).

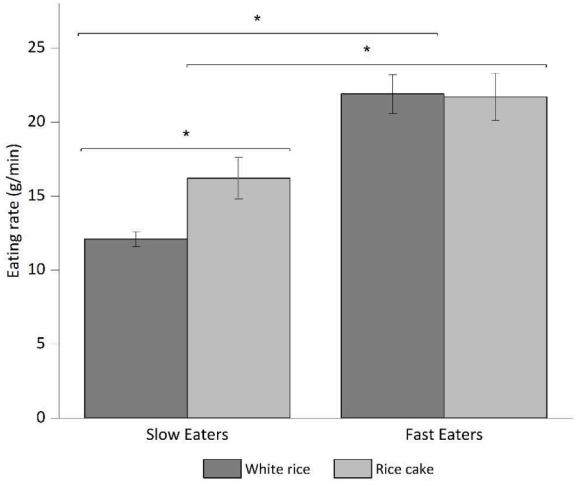


Fig 3. Eating rate of white rice (WR) and rice cake (RC) between slow (n = 19) and fast (n = 20) eaters. Paired t-test was done to compare foods. Independent t-tests were done to compare eating rate groups. *indicates significant differences at $p < 0.05$. Error bars indicate SEM.

with differences in oral processing contributing the most during the early post-prandial phase (iAUC 0-30-min). When the eating rate groups were compared for their oral processing response to a modification of food texture, slow eaters were more likely to change their eating rate than fast eaters. These preliminary findings provide new insights on how eating micro-structure varies naturally within a population to influence metabolic responses, and highlight the challenge of applying food texture to moderate these oral processing behaviours.

The oral processing behaviours observed in the current study were influenced by the texture of the two test meals, such that the "harder" food (rice cake) led to an increase in chews per bite in both the slow and fast eater groups. This finding is in line with previous findings on the role of food texture in moderating oral processing behaviours [29,41,48]. Despite large differences in meal texture, fast eaters continued to take fewer chews per bite and had a shorter oro-exposure time to maintain a consistent eating rate for each test meal (RC 21.7 g/min vs. WR 21.9 g/min). Previous reports suggest that eating rate is a highly consistent behaviour at an individual level, and the current finding suggests fast eaters are less likely to adapt their rate of eating to a modification of food

texture than slow eaters [2,49,50]. Previous research has demonstrated individuals have a similar chew rate and are less likely to adapt their eating rate in response to changes in meal duration, preferring instead to tolerate larger bolus particles at swallow [1]. Our findings show that although both slow and fast eaters had similar chew rate (chew/sec) for both test meals, fast eaters consistently maintain fewer chews per bite and a shorter oro-exposure time than slow eaters when consuming the "harder" textured meal (rice cake) which led to no difference in overall eating rate between the two test foods.

People vary considerably in their eating behaviours and the number of masticatory cycles used to prepare a bolus for safe swallow [51]. For example within a population, the number of chew-cycles required to prepare a bolus for swallow ranged from 17 - 110 for peanuts, 9 to 65 for carrots, and 14–44 for brazil nuts [27,52]. These differences in eating styles are consistent at an individual level [2] and are likely to make a sustained contribution to food digestion [53] and metabolic variability within a population. Increasing the chew-cycles per bite has been associated with a smaller bolus particle size, larger surface area and increased saliva uptake [1,25]. However, this was not shown in the current study, and despite fast eaters taking fewer chews and a shorter oro-exposure time there were no significant differences in bolus properties between groups for each test meal. It is possible that fast eaters are more efficient in breaking down solid foods during mastication using fewer chews, chewing with larger muscle force and a shorter oro-exposure time, and that this may be one of the reasons they can comfortably eat at a faster eating rate. Earlier studies have shown large inter-individual differences in bolus characteristics between different foods, while within an individual their bolus particle size for each food remained consistent [54,55]. Insufficient chewing may also impair postprandial whole-body protein metabolism in the digestion of meat proteins amongst elderly [56]. For example, one study has shown that minced beef was more rapidly digested and absorbed than beef steak, indicating that smaller food bolus particles lead to higher nutrient availability in elderly [57]. Recent research has shown that naturally chewing for a longer time for chicken and soy-based vegetarian chicken led to formation of more and smaller bolus particles and thereby increased *in vitro* protein hydrolysis compared to shorter chewing time [53]. These studies highlight that the higher degree of food degradation during the oral phase of digestion may enhance post-prandial carbohydrate and protein metabolism.

Our findings suggest that thorough mastication and longer oral exposure time had a greater influence on PPG than specific bolus properties amongst slow eaters. Longer mastication and oral exposure time may enable earlier glucose release and a higher PPG in the first 30 minutes amongst slow eaters. Although the difference in iAUC PPG were not significant, there was a trend for slow eaters to have a higher PPG than fast eaters when consuming the "harder" food. This could be explained by the fact that slow eaters took more chews/bite and had a higher saliva incorporation when consuming rice cake (Fig. 2B). This would allow for both a longer oro-sensory time and increased saliva amylase incorporation. Studies on *in vitro* digestion have shown that salivary a-amylase can hydrolyse almost 50% of starch from bread and 15–20% from pasta before being partially inactivated by the low pH of the stomach [58]. Although elevated, the iAUC remained similar between slow and fast eaters, suggesting higher insulin secretion might have occurred among slow eaters. This is in line with previous studies from our lab which showed that early PPG promoted stronger insulin secretion [9]. Although insulin response was not measured in the current study, a feeding trial conducted by Lasschuijt *et al* where participants were fed with chocolate custard showed that eating for longer duration had greater insulin production than eating for shorter duration. This could also mean that longer mastication may bring about incretin effect to attenuate glucose spike [59].

Among slow eaters, taking more chews per gram and a longer oral exposure time influenced glucose iAUC at 0-30 minutes following both test meals. Increased mastication and reduced food structure increases the total bolus surface area and makes it easier for enzymes such as salivary amylase to act on rice starch [60]. The texture properties of the rice cake have caused longer time spent chewing per bite which may enhance the effect of saliva on bolus lubrication without the associated reduction in bolus particle size or surface area. Previous findings show that starch hydrolysis is dependent on structural properties of food [26,61]. Rice cakes are produced using a homogenised paste of pulverised rice, which in turn produces structural changes to the food matrix that make the starch more readily digestible. A recent experiment showed how different processing methods of white rice products such as steamed rice, rice gruel and rice cake also yielded variations in glycaemic responses [62] Studies show that starch hydrolysis is up to 8 times faster in homogenised cooked rice than intact cooked rice [63]. This structural change may also interact with an individual's oral processing behaviour, where a longer extended eating duration extends the contact time between bolus particles and salivary amylase, and through promote starch hydrolysis during the oral phase [63]. The rice cake in our study had a sharper PPG rise in the first 30 minutes, which may be due to the nature of the easy enzymatic access to the pulverised rice starch. The dual effect of thorough mastication and pulverised food matrix might have further enhanced the glucose peak in slow eaters by allowing greater hydrolysis of starch by salivary amylase. These differences in starch structure between white rice and rice cake may help explain why the harder textured test meal failed to reduce PPG in the manner anticipated, and may also have attenuated differences in PPG due to the specific oral processing behaviour of slow and fast eaters. Findings also suggest mastication may have a greater effect on the PPG associated with intact rice grains. Future studies could look into the influence of oral processing behaviour and food texture on the physiological responses of individuals who are at risk of metabolic diseases such as diabetes.

Many previous reports suggest that food texture modifications could be applied to support diet wide reductions in eating rate, to support reduced energy intake [67-69]. Previous findings have demonstrated the effect of food texture on eating rate [32,33,41,70,71]. The current study was the first to compare the impact of food texture modifications on the oral processing behaviours of slow and fast eaters. Modifications of the food texture of the test meal had an impact on eating rate of slow eaters, whereas it did not affect eating rate of fast eaters. Moreover, the increase in hardness, adhesiveness, chewiness and Young's modulus (stiffnes) of the rice cake in comparison to white rice led to an increase, rather than a decrease, in eating rate among slow eaters. This appears to be due to the increase in average bite size due to the size of the rice cake unit. Whereas the instrumental texture and sensory texture of the test foods differed considerably, recent research has shown that food unit size and shape can strongly influence oral processing and the rate of food intake [54,72,73]. Our previous research showed significant differences between white rice and rice cakes when consumed as an individual food item rather than a meal [42], yet the current study showed that fast eaters rate of intake was unaffected by the modification of texture. These findings highlight the complexity of the relationship between food oral processing behaviour during consumption and food structure, mechanical breakdown and unit size. Two recent comprehensive reviews have summarised the effect of food rheological and mechanical properties on oral processing for individual foods [37] and composite foods [74]. Further research is now needed to understand whether food texture can produce meaningful and sustained changes to oral processing behaviours, and whether this effect is consistent among those that naturally vary as fast or slow eaters.

This study is the first to compare the impact of food texture on the oral processing behaviour of slow and fast eaters and its post-prandial glucose responses. The study strengths lie in the detailed measures of oral processing, bolus and saliva properties and post-prandial glucose responses. In addition, participants were free to eat in their normal way rather than following a prescribed eating regime as in numerous previous studies. This enabled an observational comparison of natural variations in oral processing behaviour for the two test meals differing in

texture, and provides an ecological validity to the observed differences in PPG. The results reflect participants 'usual' eating behaviour but the comparisons reported for PPG were likely influenced by differences in starch availability in the test foods. In addition, it is acknowledged that texture based differences in oral processing may have been confounded by differences in unit size of the test food, which likely dominated the underlying texture differences [72]. As the sample size for each eating rate group is relatively small the prediction models should be interpreted with caution for slow and fast eaters, as well as reported differences in post meal satiety. Due to the extensive behavioural and metabolic characterisation, the current study was limited in sample size and restricted to only two test foods. Further research is now needed to extend these preliminary findings to a larger consumer sample and wider range of test food textures in order to be able to generalise the findings of the effect of eating rate on bolus properties and post-prandial glucose responses. Finally, there are no formal or absolute cut-off values to designate an individual as a 'fast' or 'slow' eater, so comparisons in the current study are limited to the range of differences observed among the test population and food stimuli served, and were not validated with a second dataset to confirm the replicability of results. In this regard, the approach of clustering participants based on their observed eating rate is always relative to participants recruited and the food served, and remains a limitation of research in this area.

5. Conclusion

The current study demonstrated the interplay between food texture and individual's habitual eating behaviour on glycaemic response and satiety. Eating rate, oral exposure time and saliva uptake were shown to be the main contributors to an increase in post-prandial glycaemic responses in slow eaters. Modifications of food texture (white rice vs rice cake) had a considerable impact on the eating rate of slow eaters, but did not affect eating rate of fast eaters. These findings suggest a role for food texture in moderating oral processing, bolus properties and post-prandial glucose, though further research is now needed to understand how specific food texture properties can consistently influence oral processing and post-prandial responses to ingested nutrients over an extended period.

Ethics

The study was approved by the National Healthcare Group Domain Specific Review Board (NHG DSRB, Reference Number: 2018/01091), Singapore.

Funding

Supported by the Singapore Biomedical Research Council (Grant no. H18/01/a0/E11) Food Structure Engineering for Nutrition and Health.

Declaration of Competing Interest

The authors declare no conflicts of interest

Acknowledgement

The authors would like to thank Claudia Shu Ning Tang for her support with blood drawing during the data collection.

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