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Relating oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior

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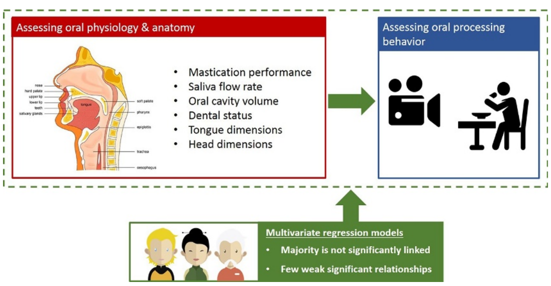
GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior. Three groups of healthy consumers were compared: Dutch, Caucasian adults (18–30 yrs, $n = 32$), Chinese, Asian adults (18–30 yrs, $n = 32$) and Dutch, Caucasian older adults (65–85 yrs, $n = 32$). Mastication performance, salivary flow rate (stimulated and unstimulated) and dental status were quantified to characterize oral physiology. Volume of oral cavity, tongue dimensions, facial anthropometry, height and weight were quantified to characterize anatomy. Oral processing behavior of three solid foods (carrot, cheese and sausage) was quantified by video recordings and eating rate (g/s), average consumption time (s), chews per bite (-) and average bite size (g) were determined. Dutch, Caucasian older adults had smaller volume of oral cavity, lower number of teeth and larger head width compared to Dutch, Caucasian adults. Chinese, Asian adults showed significantly higher mastication performance and larger head width compared to Dutch, Caucasian consumers, while dental status did not significantly differ between groups. Males had significantly larger volumes of oral cavity and larger head height and width compared to females. Dutch, Caucasian adults had a shorter average consumption time (s), less chews per bite and consumed the three foods with higher eating rate (g/s) compared to Dutch, Caucasian older adults. Chinese, Asian adults had a significantly longer average consumption time (s), more chews per bite, smaller average bite size (g) and lower eating rate (g/s) compared to Dutch, Caucasian adults. Twenty-one significant relationships were found between oral physiological and anatomical parameters and oral processing behavior. Body weight resulted in the largest β-values, indicating to be the anatomical parameter of largest influence on oral processing behavior. We conclude that only few oral physiological and anatomical parameters related with food oral processing behavior. We suggest that other factors, including cultural factors contribute to variation in food oral processing behavior between different consumer groups more than saliva flow, volume of oral cavity, mastication performance and dental status.

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1. Introduction

Food oral processing behavior is known to be affected by food properties and consumer characteristics [1], but critical details are lacking which hamper the application to consumer segmentation. There has been an increasing scientific and industrial interest in understanding food oral processing to apply this knowledge to design palatable and healthier food products for specific consumer groups [2]. During oral processing solid foods are broken down by chewing to form a bolus that can be safely swallowed [3]. When consumers cannot process and handle foods in the oral cavity sufficiently, this can result in choking and reduced food intake [4–6]. By modifying food texture eating rate can be modified, which impacts food intake [7–10]. Hence, foods for vulnerable consumers can be developed by modifying texture. Therefore, it is important to better understand the oral processing behavior of different consumer groups.

Food oral processing behavior is strongly related to rheological and mechanical properties of foods [11]. Eating rate and bite size of liquid and semi-solid foods are mainly related to the rheological properties of foods such as its viscosity. Eating rate and bite size of solids foods have been related to mechanical food properties such as modulus, stress needed to compress foods to a certain strain and instrumental texture properties obtained by texture profile analysis (TPA) [11,12]. Several suggestions have been made to explain the variation in oral processing behavior. Chen suggested that the oral individuality should not be underestimated and suggests that gender, age, race and health status influence texture perception [3]. Consumer characteristics such as age, gender and ethnicity also impact oral processing behavior.

Ageing can impact food oral processing behavior by a decline in dental status and changes in oral physiology [13–16]. A decrease in number of teeth has been found to impact mastication performance of older adults and is associated with an increase in number of chewing cycles until swallowing [17–19]. The decline in muscle forces for older adults consumers also impacts eating behavior by an increase in chewing duration and number of chews [14,16]. aging is associated with a decrease in salivation [20–23], bite force [24], tongue pressure [24–26], tongue thickness [27], volume of oral cavity [25]. These physiological parameters might contribute to food oral processing behavior and a decreased functionality with increasing age might impair effective oral processing behavior. Oral functionalities such as mastication performance and swallowing problems might also affect oral processing behavior and are therefore important to consider. Changes in anatomy during ageing, including a decrease in body height and weight and narrowing of face can also impact oral processing behavior [28–30]. Numerous studies investigated the effect of age on oral physiology [20–27]. However, only few studies investigated the link between oral physiological parameters such as dental status and mastication efficiency with food oral processing behavior. To better understand the influence of age on the link between physiology and food oral processing, further studies are needed.

Gender also impacts oral processing behavior. Males consume foods with larger bite size and at higher eating rate compared to females [13,31,32]. Males display higher masticatory frequencies [33] and shorter consumption times [13,32,34] than females. These differences in oral processing behavior between males and females might be linked to the difference in energy requirements due to differences in basal metabolic rate (BMR) [35]. We hypothesize that differences in oral processing behavior can be linked to differences oral physiology between genders. Males display higher bite force [36,37], salivary flow [21,38], cheek strength [39] and masticatory performance [40] than females. Males tend to have larger anatomical features, including body height, body weight and face size [28,30]. Other physiological parameters might also differ between genders such as oral cavity volume. To the best of our knowledge the impact of differences in oral physiology between male and female consumers has not yet been linked to food oral processing behavior.

Ethnicity also influences oral processing behavior. Chinese, Asian adults displayed lower eating rate due to smaller bite size compared to Dutch, Caucasian adults [13]. Differences in oral physiology and eating culture could explain differences in oral processing behavior between different ethnicities or nationalities. Oral physiology of Asian consumers has not been compared extensively to Caucasian consumers. Xue and Hao found that the oral cavity volume of Chinese Asian consumers was larger compared to Caucasian Americans [41]. These results from two separate studies suggest an inverse relation between volume of oral cavity and bite size. Tongue dimensions have also been suggested to be influenced by ethnicity. Tongue length of African ancestry was significant longer than tongue length of European ancestry [42]. However, no studies have investigated tongue dimensions of Caucasian compared to Asian consumers. Anatomical features of humans with different ethnicities have been extensively studied. Asians have a lower body height and body weight and wider face compared to Caucasians [30,43]. Cultural factors might also impact oral processing behavior via differences in consumption context, importance of food consumption and cutlery use [44,45].

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior of solid foods. Several physiological (salivary flow rate, mastication performance, dental status, self-reported swallowing problems) and anatomical parameters (volume of oral cavity, tongue dimensions, facial anthropometry, height and weight) were quantified in Dutch, Caucasian adults, Chinese, Asian adults and Dutch, Caucasian older adults. Oral processing behavior (consumption time, bite size, eating rate, number of chews) of three solid foods (carrot, sausage, cheese) was quantified and regression analysis performed.

2. Materials & method

2.1. Participants

Three groups of healthy consumers were recruited including 32 Dutch, Caucasian adults (20 females, mean age of 21.5 ± 1.9 yrs), 32 Dutch, Caucasian older adults (20 females, mean age of 70.4 ± 4.3 yrs) and 32 Chinese, Asian adults (20 females, mean age of 24.2 ± 2.1 yrs). The Dutch, Caucasian adults and older adults had Dutch nationality and Caucasian ethnicity. The Chinese, Asian Adults all had Chinese nationality and Asian ethnicity. Dutch, Caucasian and Chinese, Asian adults were included only when no teeth were missing. Dutch, Caucasian older adults were included only when two or less teeth were missing. Other inclusion criteria were BMI between 18.5 and 25 kg/m^2 and normal taste and smell capabilities. An inclusion questionnaire was used to ensure that the participants fit to all inclusion criteria. Participants were recruited via a study website, posters on the University Campus, social media and a participant database. Participants were invited to an information meeting and gave written informed consent to participate in the study. Participants received a financial reimbursement for participation. The study was approved by the medical ethical committee of Wageningen University (NL62694.081.17).

2.2. Oral physiological and anatomical parameters

Four oral physiological parameters (mastication performance, salivary flow, dental status, self-reported swallowing problems) and four anatomical parameters (volume of oral cavity, tongue dimensions, facial anthropometry, height and weight) were quantified by a trained researcher during one test session of 60 min. Participants were instructed to not eat, drink coffee or chew chewing gum two hours before the start of the test session.

2.2.1. Mastication performance

Mastication performance was determined as previously described [50]. Participants' ability to masticate a solid model food was quantified with the following procedure. Participants were instructed to chew 20 times on 14 cubes of Optosil (size of each cube 5 × 5 × 5 mm; total weight ~3.5 g). Optosil is an artificial test material often used as standardized model material to assess mastication performance [46]. After 20 chewing cycles participants expectorated the broken down Optosil particles. Participants were asked to rinse their mouth with water and spit this out again to ensure the majority of particles were expectorated. Particles were collected and dried overnight. After drying particles were separated manually in a petri-dish without further breaking particles. A black-white scan was made using a scanner (Canon 9000F Mark ||) and median particle size (X50) was determined using ImageJ (National Institutes of Health, USA, version 1.52a).

2.2.2. Salivary flow rate

Stimulated and unstimulated salivary flow rate were determined. Five minutes before the measurements participants were not allowed to drink and a short break was included between two measurements. For the measurement of unstimulated salivary flow rate, participants were asked to spit out their unstimulated saliva every 30 s for 5 min into a pre-weighed plastic tube. The researcher indicated every time point when the participant needed to spit out saliva. The cup was weighed before and after the test session and unstimulated saliva flow rate (mL/min) was obtained. A saliva density of 1 g/mL was assumed. A second saliva collection was done to determine stimulated saliva flow rate. Participants were asked to spit out their saliva every 30 s for 5 min while chewing on a piece of Parafilm (5 × 5 cm). Chewing on the Parafilm mimics mastication behavior and provides mechanical stimulation inducing salivation [47]. Stimulated saliva flow rate (mL/min) was determined by weighing the cup before and after the measurement.

2.2.3. Dental status

The dental status was determined by the researcher by counting total number of teeth, number of molars, number of wisdom teeth and determining the occlusion status. Occlusion status was classified according to Angle [48] into one of four categories: malocclusion class 1, 2, 3 or normal occlusion. Malocclusion class 1 included participants with the presence of a cross-bite, teeth are tilted towards cheek or tongue; or an open bite, upper and lower teeth cannot make contact; or a deep bite, upper teeth cover the lower teeth. Malocclusion class 2 included participants with the presence of an overjet indicated by the upper teeth proclining the lower teeth with more than 4 mm. Malocclusion class 3 included participants with the presence of under-bite, indicated by the proclining of the lower teeth. The fourth category of the occlusion status included participants with none of the above mentioned deviations, in other words with normal occlusion.

2.2.4. Self-reported swallowing problems

Participants filled in the EAT-10 questionnaire consisting of 10 statements on swallowing problems [49]. For every statement, participants indicated the presence and severity of swallowing problems from 0 (no problems) to 4 (severe problems) points. A total score was calculated by the sum of all 10 statements. A total score below 3 indicates no to minor swallowing difficulties. A score of 3 or larger indicates abnormal swallowing difficulties.

2.2.5. Volume of oral cavity

The volume of the oral cavity was determined with a water-retaining test [25]. Participants received a cup with 500 mL water and were instructed to keep as much water in the oral cavity as possible. Participants had to seal their lips and inflate their cheeks with water. When participants reached the maximum volume of water in their mouth, participants spat out the water in another cup. Spit out cups were weighted before and after the measurement and the differences was taken as a measure of the volume of the oral cavity (mL). It should be noted that the volume of the oral cavity determined with this method depends on (1) the anatomical volume of the oral cavity, (2) the capability to seal the mouth with the lips when it is filled with water and (3) the willingness of participants to fill their mouth with as much water as they can. Participants practiced the method before the start of the measurement. Measurements were conducted in duplicate for all participants. A paired *t*-test showed no significant difference between the two measurements ($p = 0.143$), so that the average of the two measurements was used for data analysis.

2.2.6. Tongue dimensions

Dimensions of the protruding tongue were measured by the researcher to obtain length, width and thickness of the anterior tongue. Participants were asked to protrude their tongue as far as possible and place it on top of a Plexiglas element with known dimensions (width x length mm of Plexiglas). Two pictures of the tongue were taken, (1) a frontal view of the tongue, and (2) a lateral view of the tongue. Images were analyzed with the software ImageJ to obtain length, width and thickness of the protruding, anterior tongue based on the known dimensions of the Plexiglas element.

2.2.7. Facial anthropometry, height and weight

Facial anthropometry was determined by the height and width of participants' head estimations using a frontal image of the participants, while keeping the mouth closed. Head height (mm) was measured as the distance between the bottom of the chin (menton) to the top of the head. Head width (mm) was measured as the distance between the right and left tragion, the cartilage at the front of the ear. A ratio parameter was calculated by dividing the height by the width of the head. Height and weight of participants was measured by the researcher during the information meeting.

2.3. Oral processing behavior

Oral processing behavior of carrots, sausages and cheeses was quantified. Raw carrots, old Gouda cheeses (private label), and hotdog sausages (Unox, The Netherlands) were bought at a local supermarket. Participants were offered 50 g of carrots, sausages or cheeses on a plate. Three pieces of raw carrots and three pieces of sausages were provided to offer 50 g. Cheeses were cut into one piece of rectangular shape weighing 50 g. All foods were consumed by participants using their fingers. Participants were instructed to take three bites of the food products as they would normally do. Participants were not restricted in any other way. Participants could decide on bite size, consumption time, etc. The end of consumption was indicated by the participant by raising the hand.

Participants were video recorded with a camera (Canon IXUS-500HS) positioned in front of them. Oral behavior movements were tracked by placing two stickers on the face of the participants; one sticker on the nose, as a reference point; one sticker on the chin, as a mobile point. Participants were asked to not block stickers with their hands, to not talk and to look in the direction of the camera. The distance between the mobile point and the reference point was used to extract the following oral behavior parameters using Kinovea (v0.8.15) similar to previous studies [11,13]: total eating duration (s), number of chews and eating rate (g/s). Average bite size (g) was determined for all three bites by weighing the food with a scale underneath the plate during food consumption. Average consumption time (s) was calculated by the average consumption time (s) of the three bites. The number of swallows was defined as the number of times the participants raised his or her hand, indicating one swallow. The number of chews was calculated from the vertical displacement of the jaw, calculated as the difference between the position of the stickers on the nose and chin over time. The maxima in difference between the position of the stickers on the nose and chin indicate a chewing cycle. Chews per bite was calculated by counting the maxima divided by three bites. Average bite size (g) was the average bite size of the 3 bites calculated by difference of the weight of the sample before and after consumption and dividing it by three. Eating rate (g/s) was calculated by dividing bite size (g) of all 3 bite by the consumption time (s) of all 3 bites.

2.4. Statistical data analysis

Data was analyzed with SPSS (IBM SPSS statistics, version 23). Normality of the variables was checked and non-normal distributed data was log-transformed. The data is presented as mean value and standard deviation (SD). Multivariate ANOVA's were conducted separately for salivary flow rate (unstimulated and stimulated saliva flow rate), dental status (number of teeth, number of molars, number of wisdom teeth), tongue dimensions (tongue length, width and thickness), facial anthropometry (head height and width), height and weight. Height was included as covariate in the multivariate ANOVA for head height, weight was included as covariate for head width. Separate univariate ANOVA's were conducted for EAT-10 score, average volume of oral cavity and mastication performance (median particle size). Height and weight of subjects were included as covariates for average volume of oral cavity. Consumer group and gender were included as fixed factor for all analyses. Post-hoc pairwise comparisons were performed for the multivariate and univariate ANOVA's using Bonferroni's adjustment. Two Chi-Square test were conducted, (1) to relate occlusion status to consumer group and (2) to relate occlusion status to gender.

Four multivariate ANOVA's were performed for all oral processing parameters (consumption time (s), chews per bite, average bite size (g), eating rate (g/s)). Oral processing parameters for all three foods (carrot, sausage, cheese) were included as dependent variables and the consumer groups and gender as fixed factors and food as covariate. Post-hoc pairwise comparisons were performed using Bonferroni's adjustment.

A multivariate linear regression was conducted to study the link between parameters describing oral physiology and anatomy and oral processing parameters. All oral processing, physiological and anatomical parameters were standardized to allow for comparison of standardized β-coefficients. All oral processing parameters for all products and all three consumer groups were included as dependent variables and 14 physiology and anatomy parameters were included as covariates. Multicollinearity of the variables was checked by visual inspection of the data by bi-plots, highly correlated variables ($r > 0.7$) and high variance inflation factor (VIF > 5). Based on these variables, number of wisdom teeth and head width were removed from analysis. Pearson correlations of all 4 oral processing parameters were conducted to explore inter-relationships for all oral processing parameters. The within consumer group variation in oral processing behavior and oral physiology and anatomy was checked with boxplots and standard deviations of all parameters.

3. Results

3.1. Comparison of oral physiology of Chinese, Asian and Dutch, Caucasian adults and Dutch, Caucasian older adults

3.1.1. Mastication performance

Mastication performance measured by median particle size (X50) was significantly affected by consumer group ($F(2,90) = 5.4$, $p = .006$, Fig. 2). Chinese, Asian adults displayed a significant smaller median particle size compared to Dutch, Caucasian adults ($p = .029$) and Dutch, Caucasian older adults ($p = .009$). Dutch, Caucasian adults and Dutch, Caucasian older adults did not significantly differ in median particle size. The masticated samples of the Chinese, Asian adults had an average median particle size of 0.2 mm. Dutch, Caucasian adults had an average median particles size of 0.3 mm, indicating a better mastication performance by the Chinese, Asian adults compared to Dutch, Caucasian adults. Mastication samples of Dutch, Caucasian older adults consumers had an average median particle size of 0.3 mm. No significant effect of gender on median particle size was found, indicating no difference in mastication performance between gender.

3.1.2. Saliva flow rate

A significant effect of consumer group on stimulated saliva flow rate ($F(2,90) = 3.3$, $p = .04$) was found (Fig. 3), with Dutch, Caucasian older adults (1.6 ± 0.7 mL/min) having a significant higher stimulated saliva flow rate compared to Dutch, Caucasian adults (1.3 ± 0.5 mL/min). No significant differences in saliva flow rate were found between Dutch, Caucasian and Chinese, Asian adults; and between the Dutch, Caucasian older adults and the Chinese, Asian adults. No significant effect of consumer group was found on unstimulated salivary flow rate (Fig. 3) and no gender effect was found for both saliva flow rates. Concluding, stimulated saliva flow rate only differed between Dutch, Caucasian older adults and Dutch, Caucasian adults.

3.1.3. Dental status

Dental status was significantly different between consumer groups for all three dental parameters, number of teeth ($F(2,90) = 11.7$, $p < .001$), number of molars ($F(2,90) = 3.4$, $p = .036$) and number of wisdom teeth ($F(2,90) = 5.0$, $p = .009$). As expected, Dutch, Caucasian older adults had a significant lower number of teeth compared to both Dutch, Caucasian adults ($p < .001$) and Chinese, Asian adults ($p = 003$). Dutch, Caucasian older adults had on average 27.9 teeth, Dutch, Caucasian adults had 29.5 teeth and Chinese, Asian adults had 29.0 teeth. The difference in total number of teeth is caused by the difference in number of wisdom teeth. The number of wisdom teeth was significantly lower for Dutch, Caucasian older adults consumers compared to Dutch, Caucasian adults ($p = .007$). Dutch, Caucasian adults had on average 0.4 wisdom teeth, Dutch, Caucasian adults had 1.5 wisdom teeth and Chinese, Asian adults had 1.0 wisdom teeth. Dutch, Caucasian older adults did not significantly differ in number of molars compared to both Dutch, Caucasian adults ($p = .077$) and Chinese, Asian adults ($p = .077$). Dutch, Caucasian older adults had on average 15.7 molars, Dutch, Caucasian adults had 16.0 molars and Chinese, Asian adults had 16.0 molars. A significant effect of gender was found for the number of wisdom teeth ($F(1,90) = 4.9$, $p = .029$), with females having on average 0.8 wisdom teeth and males 1.3 wisdom teeth. To summarize, minor differences in dental status were found especially between the Dutch, Caucasian adults and Dutch, Caucasian older adults.

3.1.4. Self-reported swallowing problems

No significant effect of consumer group or gender was found for the self-reported swallowing problems ($p > .05$). Eighty-one participants out of 96 had a score between 0 and 2 falling in the group of consumers with no to minor swallowing problems [49]. Fifteen participant had a score of 3 to 9 falling in the group with swallowing problems.

3.1.5. Volume of oral cavity

Volume of oral cavity was significantly affected by consumer group ($F(2,87) = 15.9$, $p < .05$, Fig. 4) and gender ($F(1,87) = 13.0$, $p < .05$). Dutch, Caucasian older adults had a significant smaller volume of oral cavity compared to Dutch, Caucasian adults ($p = .001$) and Chinese, Asian adults ($p = .04$). Dutch, Caucasian older adults had an average oral cavity of 72 mL, Dutch, Caucasian adults had an average oral cavity of 87 mL and Chinese, Asian adults of 86 mL. Females consumers had an average oral cavity of 75 mL and males of 93 mL. To summarize, differences in volume of oral cavity are found between consumer groups and gender.

3.1.6. Tongue dimensions

A consumer effect was found for the thickness of the anterior tongue ($F(2,90) = 9.6$, $p < .001$), with Dutch, Caucasian older adults having significantly thicker anterior tongues compared to Dutch, Caucasian adults ($p < .001$) and Chinese, Asian adults ($p = .002$). Dutch, Caucasian older adults had an average thickness of 23.9 mm, Dutch, Caucasian adults consumers had an average of 19.8 mm and Chinese, Asian adults had an average of 20.1 mm. The length and width of the tongue was not significantly different between the three groups. No effect of gender was found for any of the tongue measurements. The results indicate minor differences in thickness of the anterior tongue between consumer groups.

3.1.7. Facial anthropometry, height and weight

Consumer group had a significant effect on the head width ($F(2,89) = 8.9$, $p < .001$) and the ratio height-width ($F(2,95) = 12.2$, $p < .001$). Dutch, Caucasian adults had a significant smaller head (125.1 mm compared to Dutch, Caucasian older adults (131.0 mm, $p = .048$) and Chinese, Asian adults (135.6 mm, $p < .001$). Chinese, Asian adults had a lower ratio height-width (factor: 1.59) compared to Dutch, Caucasian adults (factor: 1.90, $p < .001$) and Dutch, Caucasian older adults (factor: 1.65, $p = .013$). Gender had a significant effect on head height ($F(1,89) = 14.2$, $p < .001$) and head width ($F(1,89) = 5.2$, $p < .05$). Females had a significant smaller head height (207.4 mm) and head width (127.8 mm) compared to males (height: 220.4 mm, $p < .001$; width: 133.4 mm, $p = .025$). The results indicate Dutch, Caucasian adults have a smaller and more rectangular shape head compared to Chinese, Asian adults and Dutch, Caucasian older adults. Females were found to have a smaller head, both height and width, compared to males.

Consumer group had a significant effect on height ($F(2,95) = 8.6$, $p < .001$) and weight ($F(2,95) = 4.9$, $p = .010$). Dutch, Caucasian adults were significantly taller (1.77 m) compared to Dutch, Caucasian older adults (1.71 m, $p = .012$) and Chinese, Asian adults (1.69 m, $p < .001$). Dutch, Caucasian adults had a significantly higher weight (68.9 kg) compared to Chinese, Asian adults (62.8 kg, $p = .013$). Gender had a significant effect on height ($F(1,95) = 43.4$, $p < .001$) and weight ($F(1,95) = 39.0$, $p < .001$). Females were significantly shorter (1.63 m) and weigh less (61.2 kg) compared to males (height: 1.78 m, $p < .001$; weight: 71.8 kg, $p < .001$). To summarize, Dutch, Caucasian adults are taller and heavier compared to Chinese, Asian adults. Females are shorter and weigh less compared to males.

3.2. Comparison of oral processing behavior of solid foods by Chinese, Asian and Dutch, Caucasian adults and Dutch, Caucasian older adults

3.2.1. Average consumption time

Average consumption time (s) was significantly affected by consumer group ($F(2,90) = 10.2$, $p < .001$, Fig. 5A), with Dutch, Caucasian adults consumers having a shorter average consumption time (19.3 s) of the solid foods compared to Dutch, Caucasian older adults (27.7 s, $p < .001$) and Chinese, Asian adults (25.7 s, $p = .009$). No effect of gender on average consumption time (s) was found. Product type also affected average consumption time ($F(2,90) = 20.5$, $p < .001$) with the sausage resulting in the shortest average consumption time of 21.4 s compared to 25.0 s for cheese ($p < .001$) and 26.3 s for carrots ($p < .001$). No significant interaction effect of consumer group and product was found. To summarize, Dutch, Caucasian adults have the shortest consumption time until swallowing compared to Dutch, Caucasian older adults and Chinese, Asian adults.

3.2.2. Chews per bite

A significant effect of consumer group on the chews per bite was found ($F(2,90) = 10.7$, $p = .003$, Fig. 5B). Dutch, Caucasian adults had significantly less chews per bite (27.0 chews) compared to Dutch, Caucasian older adults (39.9 chews, $p < .001$) and Chinese, Asian adults (37.9 chews, $p = .001$). No significant effect of gender on chews per bite was found. Product type significantly affected chews per bite ($F(2,90) = 5.9$, $p = .003$), with the sausage being consumed with less chews compared to carrots ($p = .013$). Consumers needed on average 31.8 chews for the sausage and 39.8 chews for carrots. No significant interaction effect of consumer group and product was found. Similar to the results of consumption time, Dutch, Caucasian adults had the least number of chews per bite compared to Dutch, Caucasian older adults and Chinese, Asian adults.

3.2.3. Average bite size

A significant effect of consumer group on average bite size (g) was found ($F(2,90) = 8.2$, $p = .001$, Fig. 5C). Chinese, Asian adults having a significant smaller average bite size (6.9 g) compared to Dutch, Caucasian older adults (6.7 g, $p = .003$) and Dutch, Caucasian adults (5.4 g, $p = .001$). Gender had a significant effect on average bite size (g) ($F(1,90) = 5.6$, $p = .020$), with males having a larger average bite size (7.2 g) compared to females (5.8 g). An effect of product on average bite size (g) was found ($F2,90) = 58.788$, $p < .001$). Average bite size of sausage was significantly larger (bite size = 8.0 g) than average bite size of carrot ($p < .001$, bite size = 5.3 g) and cheese ($p < .001$, bite size = 5.8 g). An significant interaction effect of Consumer and Product was found for average bite size ($F(4,90) = 15.3$, $p < .001$). This implies that the average bite size of the different consumer groups depended on the product. To summarize, Chinese, Asian adults had a smaller average bite size compared to both Dutch, Caucasian consumer groups. Males had a larger average bite size compared to females.

3.2.4. Eating rate

Consumer group had a significant effect on eating rate (g/s) ($F(2,90) = 23.1$, $p < .001$, Fig. 5D), with Dutch, Caucasian adults showing a higher eating rate (0.40 g/s) compared to Dutch, Caucasian older adults ($p < .001$, 0.27 g/s) and Chinese, Asian adults ($p < .001$, 0.22 g/s). An effect of gender on eating rate (g/s) was found ($F(1,90) = 9.0$, $p = .004$), males (0.34 g/s) had a higher eating rate than females (0.10 g/s). Product had a significant effect on eating rate (g/s) ($F(2,90) = 166.2$, $p < .001$), with the consumption of the sausage resulting in a higher eating rate compared to the consumption of carrots ($p < .001$) and cheese ($p < .001$). Participants had an average eating rate of 0.43 g/s for sausage, 0.22 g/s for carrot and 0.25 g/s for cheese. An significant interaction effect of Consumer and Product was found for eating rate (g/s) ($F(4,90) = 22.4$, $p < .001$). This implies the eating rate (g/s) of the different consumer groups depends on the product. Similar to the results of bite size, Dutch, Caucasian adults had the higher eating rate.

Several of the oral processing parameters were highly correlated, since several parameters are derived from other oral processing parameters (Table 1), including consumption time and chews per bite with a Pearson correlation of 0.899 ($p < .001$). Box plots are shows in Fig. 1A and B to visualize variations in oral processing behavior within consumer groups. Dutch, Caucasian older adults group showed a larger variation in average consumption time and chews per bite compared to Dutch, Caucasian adults (Fig. 1A and B).

Table 1
Pearson correlations of the four oral processing parameters.

	Consumption time (s)	Bite size (g)	Eating rate (g/s)	Chews per bite (-)
Consumption time (s)	–			
Bite size (g)	0.255*	–		
Eating rate (g/s)	−0.448*	0.639*	–	
Chews per bite (-)	0.899*	0.227*	−0.422*	–

* Correlation is significant with $p < .001$.

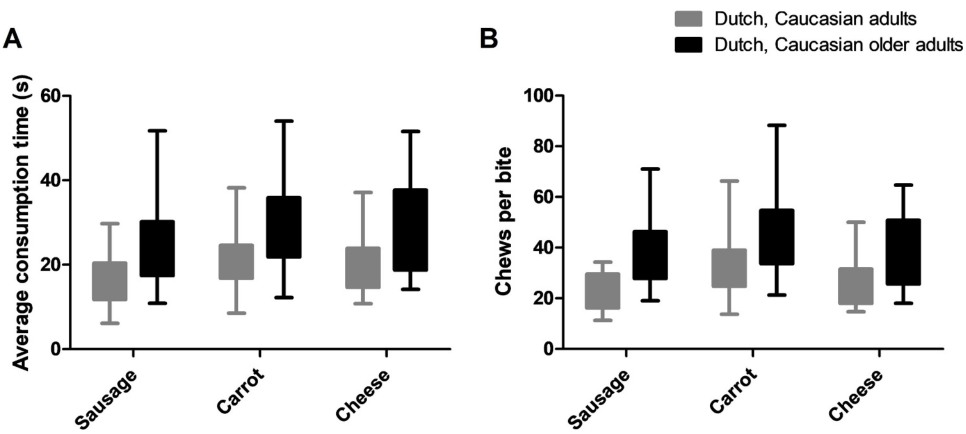

Fig. 1. Variation in oral processing behavior of Dutch, Caucasian adults and Dutch, Caucasian older adults determined by (A) average consumption time (s) and (B) chews per bite.

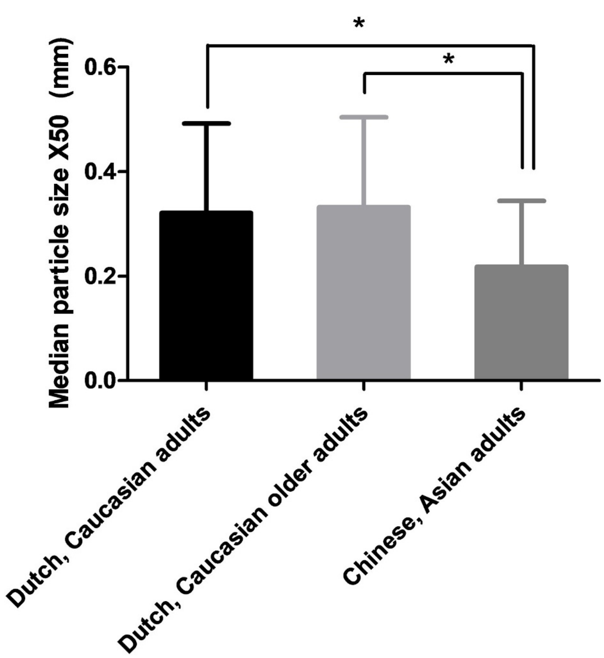

Fig. 2. Mastication performance quantified by the median particle size (X50) of Optosil cubes chewed 20x by Dutch, Caucasian adults ($n = 32$, 20 females, 18–30yrs), Dutch, Caucasian older adults ($n = 32$, 20 females, 65–85yrs) and Chinese, Asian adults ($n = 32$, 20 females, 18–30yrs). Error bars indicate standard deviation.

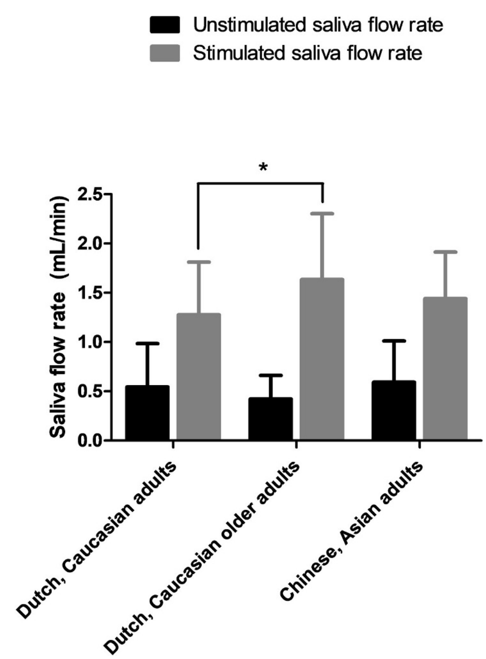

Fig. 3. Unstimulated and stimulated saliva flow rate (mL/min) of Dutch, Caucasian adults ($n = 32$, 20 females, 18–30yrs), Dutch, Caucasian older adults ($n = 32$, 20 females, 65–85yrs) and Chinese, Asian adults ($n = 32$, 20 females, 18–30yrs). * Effect is significant at $p < .05$. Error bars indicate standard deviation.

3.3. Relationships between parameters describing oral physiology and oral processing behavior of solid foods

A multivariate linear regression was performed to assess the relationships between the 14 parameters describing oral physiology and the four oral processing behavior parameters per product (three products).

Stimulated saliva flow rate was positively related to bite size (g) of cheese ($\beta = 0.33$, $p < .01$), indicating a higher stimulated saliva flow rate is associated to an increased bite size of the cheese product.

Number of molars is negatively related to average consumption time (s) of carrot ($\beta = -0.23$, $p < .05$) and cheese ($\beta = -0.21$, $p < .05$). Number of molars is also negatively related to chews per bite of sausage ($\beta = -0.19$, $p < .05$), carrots ($\beta = -0.24$, $p < .05$) and cheese ($\beta = -0.21$, $p < .05$). Average bite size (g) of cheese is negatively related to number of molars ($\beta = -0.21$, $p < .05$). A positive relationship was found between number of molars and eating rate (g/s) of sausage ($\beta = 0.20$, $p < .05$) and carrot ($\beta = 0.34$, $p < .001$). Concluding, a higher number of molars is associated to a shorter consumption time, fewer chews per bite, smaller bite size and higher eating rate. However these results are not consistently found for all products.

Tongue thickness is positively related to average bite size (g) of cheese ($\beta = 0.18$, $p < .05$) and eating rate (g/s) of carrots ($\beta = 0.17$, $p < .05$). The results suggest an increased thickness of the tongue is associated with increased bite size and eating rate, however only for carrots.

Volume of oral cavity is positively related to average bite size (g) of sausage ($\beta = 0.30$, $p < .01$), suggesting an increased volume of oral cavity is associated with increased bite size. Fig. 6 visualizes the relationships between the volume of oral cavity and average bite size (g).

Mastication performance, assessed with median particle size, is negatively related to average consumption time (s) ($\beta = -0.22$, $p < .05$) and chews per bite ($\beta = -0.23$, $p < .05$) of cheese. The results indicate a good mastication performance is associated with a

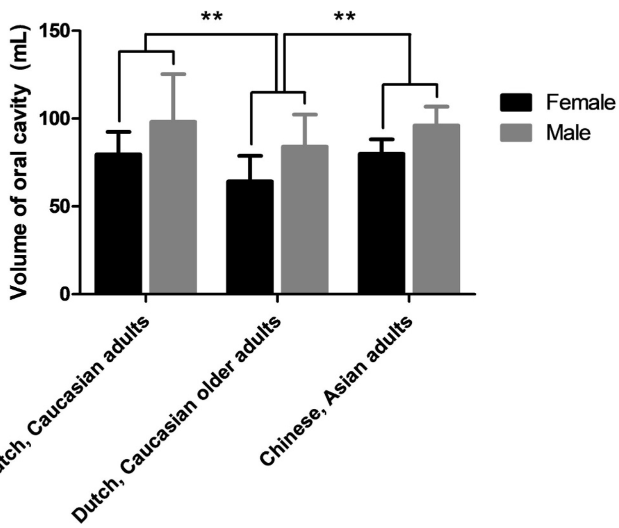

Fig. 4. Volume of oral cavity (mL) of Dutch, Caucasian adults (n = 32, 20 females, 18–30yrs), Dutch, Caucasian older adults (n = 32, 20 females, 65–85yrs) and Chinese, Asian adults (n = 32, 20 females, 18–30yrs). ** Effect is significant at $p < .01$. Error bars indicate standard deviation.

shorter consumption time and less chews per bite.

Body weight was positively related to average bite size (g) of sausage (β = 0.46, $p < .01$), carrot (β =0.42, $p < .05$) and cheese

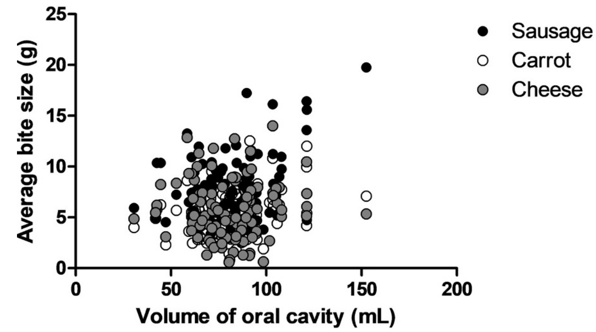

Fig. 6. Relationship between volume of oral cavity and bite size of sausage.

(β = 0.48, $p < .01$), suggesting an increase body weight is associated with an increased bite size. Fig. 7 visualizes the relationships between the body weight and average bite size (g).

Height of the head was positively related to eating rate (g/s) of carrot (β = 0.19, $p < .05$), indicating an increased head by height results in a higher eating rate. The ratio parameter of height by width of the head was positively related to chews per bite of sausage (β = 0.21, $p < .05$) and cheese (β = 0.29, $p < .05$), and average bite size (g) of cheese (β = 0.31, $p < .05$). These results indicate a more rectangular shape of head results in more chews and a larger bite size.

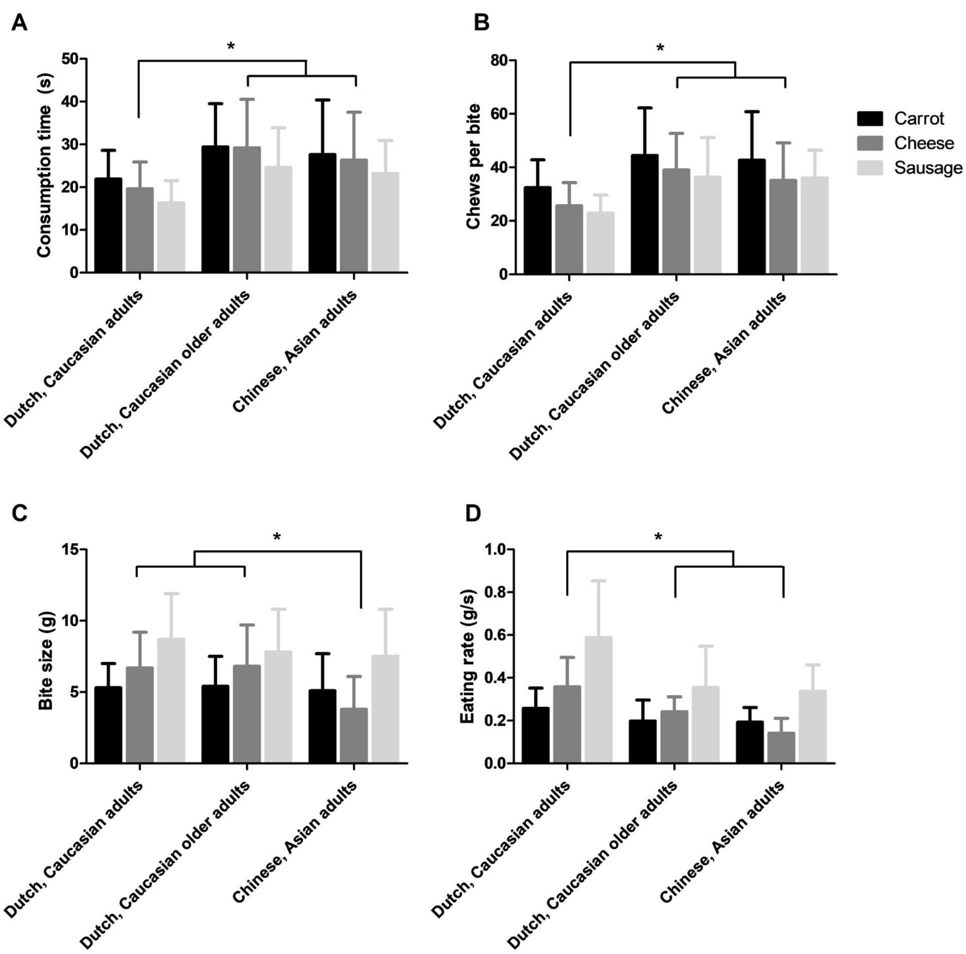

Fig. 5. Oral processing behavior of raw carrots, cheese and sausages determined by (A) consumption time, (B) chews per bite, (C) bite size and (D) eating rate for Dutch, Caucasian adults (n = 32, 20 females, 18–30yrs), Dutch, Caucasian older adults (n = 32, 20 females, 65–85yrs) and Chinese, Asian adults (n = 32, 20 females, 18–30yrs). ** Effect is significant at $p < .01$. Error bars indicate standard deviation.

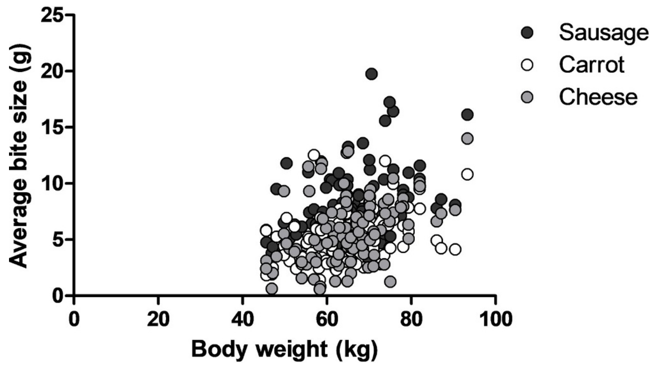

Fig. 7. Relationship between body weight and bite size of sausage, carrot and cheese.

4. Discussion

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior of solid foods. Considerable differences were found between age groups, gender and ethnicities in oral physiology, oral anatomy and oral behavior. Only few significant relationships were found between parameters describing oral physiology, anatomy and food oral processing behavior of solid foods by consumer varying in age, gender and ethnicity. A total of twenty-one significant relationships were found between the selected oral physiological and anatomical parameters and the oral processing behavior out of 168 relationships that were tested.

Body weight showed the largest β-values with the average bite size of all three foods. The association between eating rate and body weight could result in a higher body weight. Stimulated saliva flow rate related the strongest with bite size of cheese as indicated by one of the largest β-values, suggesting to be of large importance to the oral processing behavior. The results indicated a positive relationship ($\beta = 0.33$) of stimulated saliva flow rate on the average bite size of cheese. Since saliva is essential for bolus formation, it was expected that high saliva flow rate could facilitate oral processing and possibly reduce consumption time. Number of molars was found to be negatively related to consumption time, chews per bite and average bite size, and positively related to eating rate. This is in line with previous research indicating the strong impact of dental status on oral processing behavior [17–19]. Since we included relatively healthy participants, the other dental status parameters did not differ much and therefore did not impact oral processing behavior. The volume of oral cavity and bite size were only found to be significantly related for sausages. A trending effect was found for carrot ($\beta = 0.20$, $p = .057$), suggesting that volume of oral cavity might also influence bite size for other products. Mastication performance was negatively related to consumption time and chews per bite for cheese. This relationship suggests that a good mastication performance can assist oral processing by reducing consumption time and chews per bite. The results indicate that body weight, number of molars and stimulated salivary flow rate have the relative largest impact on oral processing behavior.

Since the measured physiological and anatomical parameters seem to explain the variation in oral processing behavior to a limited extend, other physiological parameters not measured in this study, may also explain some of the variation in oral processing behavior. For example, maximum bite force is a physiological measurement which has been often investigated and found to have a large variability amongst individuals. However, the maximum bite force might not be representative of the bite force needed to break down foods. Forces required to break down food products average 8 N/cm^2 for soft foods such as feta cheese [50] and 60 N/cm^2 for firmer foods, such as apples [51]. Maximum bite forces are much higher. Healthy adults have an range in bite force of 284 - 778 N [52–55]. The maximum bite force is not necessary for fracturing food products. The comfortable maximum bite force may be a more relevant oral physiological measure that links to oral processing behavior compared to maximum bite force. Maximum tongue pressure is another physiological measurement which has been often investigated and found to have a large variability amongst individuals [25,56,57]. Several studies have found a decrease in maximum tongue pressure with increasing age [25,58,59]. Similar to the maximum the bite force, this maximum tongue pressure is not always necessary during oral processing and was therefore not selected to quantify in the current study. Other measurements of tongue pressure might be more relevant for oral processing behavior of foods, including in vivo measurements of tongue pressure [56] and mean swallowing pressure of the tongue [26]. Another possible factor could be the large inter-individual variation in saliva composition that can influence sensory perception and liking [60,61]. Mosca and colleagues found that both age and ethnicity impact protein concentration, with Asians having a higher protein concentration compared to Caucasians; and protein concentration increasing with age [62]. Understanding the saliva composition for different consumer groups might give insights in the link with product perception.

Cultural parameters could also be important for oral processing behavior of consumers with different ethnicities. In Asian cultures, a meal is an important family activity, incorporated in many family traditions and often eaten together [45]. Consumption with others is known to influence eating behavior and increases food intake [44]. This cultural factor could have influenced the oral processing behavior of the Chinese, Asian adults in the current study, however the exact influence of consumption context has not been tested. Secondly, the common use of chopsticks during food consumption could have affected the processing behavior of the Chinese, Asian adults in our study. Chinese, Asian adults are used to consumption with chopsticks, which are known to result in smaller bite sizes compared to consumption with cutlery [63]. The Chinese, Asian adults might have adapted their bite size in this study to their regular bite size with chopsticks. However, it is not known whether the smaller bite size of the Chinese, Asian adults is due to a cultural factor, such as the use of chopsticks.

Ageing was found to impact both oral physiology and oral processing behavior. Dutch, Caucasian older adults consumed longer and with more chews until swallowing compared to Dutch, Caucasian adults, similar to previous studies [13,14,16]. The decline in muscle mass and dental status during aging, results in a reduced muscle activity during consumption for older consumers and consequently an adaptation of oral processing behavior by chewing more and for a longer time before swallowing [14,16]. The current study found that Dutch, Caucasian older adults had a smaller oral cavity and higher stimulated salivary flow compared to Dutch, Caucasian adults. The volume of oral cavity for young (87 mL) and old consumers (72 mL) are similar to previous research, with 78 mL and 56 mL respectively [25]. The outcome of the water-holding method, used in both studies, is dependent on anatomical volume, capability to seal lips and inflation of the cheeks and willingness of participants to keep as much water as possible in their oral cavity. Therefore the outcome of the method does not necessarily reflect a direct measurement of the volume of oral cavity. Several studies found a decrease in salivary flow rate with increasing age [20–23], which is in contrast to the findings of this study which observed higher stimulated salivary flows for the Dutch older adults. The current study found only a single effect of $p = .04$, while no significant effects were found for the unstimulated salivary flow rate. This marginal effect could be an error due to the small sample size of the current study, 32 subjects per consumer group were included, while previous studies included a minimum of 75 subjects. Minor differences in the thickness of the tongue were found between Dutch, Caucasian adults and Dutch, Caucasian older adults, with a larger thickness for the Dutch, Caucasian older adults. These differences are in contradiction to previous research that found a negative correlation of tongue thickness and age [27].

However, the study of Tamura and colleagues only included older adults consumers with an age of 80.3 ± 7.9 yrs. Therefore, a clear comparison of tongue length between young and old consumers has not been made before. The results of the current study could reflect actual physiological differences, but may also be an artefact of the used method, i.e. the willingness of the participant to stick out their tongue, could have affected the results of the tongue dimensions. Therefore, this method is highly influential by the participants execution of the method and is hard to standardize. The authors recommend to use other, objective methods which can be standardized to assess the tongue dimensions, such as ultrasonography. To reduce experimental costs, this method was not selected for the current study. Dutch, Caucasian older adults showed to have a larger variation in average consumption time and chews per bite compared to the Dutch, Caucasian adults (Fig. 1A and B). The older adults population is known to be a heterogeneous group having a wide range of physical abilities [24,64,65]. This has resulted in a large variation in consumption time and chews per bite for the older adults in the current study. The current study does not have a large enough sample size to investigate the heterogeneity of older adults.

Gender had an influence on oral processing behavior. Differences in oral processing behavior could be due to differences in oral physiology. Males had a larger average bite size (g) and higher eating rate (g/s) compared to females, which is in line with several previous studies [13,31,32]. Males had a larger oral cavity and slightly more wisdom teeth compared to females. The influence of gender on volume of oral cavity has not been compared before and therefore this is the first study to find a larger oral cavity for males than females. The larger oral cavity could be related to the height of participants, this was positively correlated ($r = 0.367$, $p < .001$). The larger oral cavity for males could also explain the larger number of wisdom teeth, due to a larger capacity for additional teeth. The volume of oral cavity and the number of wisdom teeth showed a weak positive correlation ($r = 0.247$, $p = .015$). A previous study has found a higher salivary flow and masticatory performance for males compared to females [21,40]. The females in the current study did have a lower stimulated and unstimulated salivary flow compared to males, however these differences were not significantly different. This could be due to the smaller group of participants in the current study compared to the study of Percival et al. [21].

Oral processing behavior and oral physiology was affected by ethnicity. Asian Chinese consumers had shorter average consumption time (s), more chews per bite, smaller average bite size (g) and lower eating rate (g/s) compared to young Caucasian Dutch consumers. Similar differences in average bite size (g) and eating rate (g/s) have been found in a previous study [13], but the difference in consumption time (s) and chews per bite has not been reported yet. This could be due to the type of products used in both studies, with the previous study using 18 foods including liquids, semi-solids and solids while the current study only included carrots, cheese and sausage. The relative low eating rate for the Chinese, Asian adults (0.22 g/s) is driven by the low eating rate for the cheese (0.14 g/s), compared to the carrot (0.19 g/s) and sausage (0.34 g/s). Differences in the parameters describing oral physiology were found for the mastication performance, with Asian Chinese consumers resulting in a better mastication performance. These differences have not been studied yet. A better mastication performance could indicate an easier oral processing behavior, however this did not reduce their consumption time. Chinese Asian consumers were found to have a larger oral cavity compared to Caucasian Americans [41]. However this difference was not found in the current study with an average oral cavity of 87 mL for the Dutch, Caucasian adults and 86 mL for the Chinese, Asian adults. The lack of difference could be due to the execution of the method, i.e. the willingness or capability of the participants to keep as much water in their mouth as possible. The Chinese participants might have felt less comfortable to take a lot of water in their mouth, compared to the Dutch participants who might be more familiar with sensory testing.

The sample size of the three consumer groups in this study is relatively low and could be a possible cause of the minor effect of age, gender and ethnicity on oral physiology and oral processing behavior. Futures studies should validate the findings of the current study by including a larger sample size.

5. Conclusions

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior. Understanding the oral processing behavior is important as ineffective processing of foods might result in choking and digestion problems. Eating rate is also known to be positively related to food intake and consequently impacts body weight [66,67]. Oral physiology and oral processing behavior differed between consumer groups and genders. Mastication performance, stimulated salivary flow rate and volume of the oral cavity showed clear differences between the three consumer groups. Oral processing behavior of raw carrot, cheese and sausage differed for the three consumer groups, with differences for consumption time, chews per bite, bite size and eating rate. Several of the physiological and anatomical parameters were related to the oral processing parameters. Body weight resulted in the largest β-values with a positive relationship with bite size. The parameters did not always show consistent relationships across products. The parameters describing oral physiology and anatomy explain the variation in oral processing behavior only to a limited extend. Other physiological parameters and other cultural factors might be more suitable to explain variation in oral processing behavior between consumer groups differing in age, gender and ethnicity.

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