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Influence of oral processing on appetite and food intake – A systematic review and meta-analysis

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ABSTRACT

Food delivers energy, nutrients and a pleasurable experience. Slow eating and prolonged oro-sensory exposure to food during consumption can enhance the processes that promote satiation. This systematic review and meta-analysis investigated the effects of oral processing on subjective measures of appetite (hunger, desire to eat) and objectively measured food intake. The aim was to investigate the influence of oral processing characteristics, specifically "chewing" and "lubrication", on "appetite" and "food intake". A literature search of six databases (Cochrane library, PubMed, Medline, Food Science and Technology Abstracts, Web of Science, Scopus), yielded 12161 articles which were reduced to a set of 40 articles using pre-specified inclusion and exclusion criteria. A further two articles were excluded from the meta-analysis due to missing relevant data. From the remaining 38 papers, detailing 40 unique studies with 70 subgroups, raw data were extracted for meta-analysis (food intake $n = 65$, hunger $n = 22$ and desire to eat ratings $n = 15$) and analyzed using random effects modelling. Oral processing parameters, such as number of chews, eating rate and texture manipulation, appeared to influence food intake markedly but appetite ratings to a lesser extent. Meta-analysis confirmed a significant effect of the direct and indirect aspects of oral processing that were related to chewing on both self-reported hunger (−0.20 effect size, 95% confidence interval CI: −0.30, −0.11), and food intake (−0.28 effect size, 95% CI: −0.36, −0.19). Although lubrication is an important aspect of oral processing, few studies on its effects on appetite have been conducted. Future experiments using standardized approaches should provide a clearer understanding of the role of oral processing, including both chewing and lubrication, in promoting satiety.

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List of non-standard abbreviations

WHO	World Health Organization
FSTA	Food Science and Technology Abstracts
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PICOS	Population, Intervention, Comparison, Outcome, and Setting
DEBQ	Dutch Eating Behavior Questionnaire
TFEQ	Three Factor Eating Questionnaire
VAS	Visual Analogue Scales
M/F	Male/Female
NA	Not Applicable/Available
UW	Underweight, BMI <18.5 kg/m^2
NW	Normal Weight, BMI of 18.5–24.9 kg/m^2
OW	Overweight, BMI of 25–29.9 kg/m^2
OB	Obese, BMI ≥30 kg/m^2
RE model	Random Effects model
ME model	Mixed Effects model
DE	Desire to Eat

1. Introduction

Food intake is a motivated behavior essential to survival by providing energy and nutrients to the body. However, chronic energy intake in excess of requirements leads to a positive energy balance, and in the long term, contributes to obesity (World Health Organization, 2000). For the first time in human history, the proportion of the population that is obese (body mass index, BMI ≥30 kg/m^2) and overweight (BMI of 25 - <30 kg/m^2) has surpassed that which is underweight (BMI <18.5 kg/m^2). The WHO (2016) estimates about 1.9 billion adults are overweight globally with >30% among them being obese (World Health Organization, 2016). Consumers are encouraged to eat less and move more (Hill, 2006) and food manufacturers have been working to reformulate foods to reduce their energy content whilst maintaining or improving satisfaction for example, by increasing oral processing to enhance satiation and satiety (Hetherington et al., 2013).

While the terms "satiation" and "satiety" are often used synonymously in the literature, they encompass different components of the satiety cascade. Satiation is defined as the processes leading to meal termination, and therefore includes all events taking place during the course of the eating occurrence and controls meal size (Blundell et al., 2009). On the other hand, satiety is described as the inhibition of further eating as well as the suppression of feelings of hunger (Blundell et al., 2009; Blundell et al., 2010). Satiety has an influence on the time between two meals during which hunger, which has been suppressed, then begins to increase until the next eating occurrence. Constructs such as hunger and desire to eat represent approach behaviors indicative of appetite or readiness to eat (Stubbs et al., 2000). During sham feeding studies in humans, chewing fails to reduce hunger and desire to eat (subjective appetite) but produces sensory specific satiety and decreases food intake (Nolan & Hetherington, 2009). Therefore, in examining the effects of oral processing it is important to attend to behavioural markers of both appetite and satiation.

During food consumption, food is processed in the mouth from first bite to swallowing, primarily involving reduction in the particle size driven by "chewing", and the incorporation of saliva to form a swallowable bolus through "oral lubrication" (Chen & Stokes, 2012; Chen, 2009; Sarkar & Singh, 2012; Sarkar, Ye, & Singh, 2017). Depending on the nature of food and its oral interactions, the length or intensity of the oro-sensory exposure (i.e. oral residence time) may vary (Ferriday et al., 2016; Forde, Kuijk, Thaler, de Graaf, & Martin, 2013; Laguna & Sarkar, 2016; Viskaal-van Dongen, Kok, & de Graaf, 2011). For instance, in previous studies food manipulations to influence oral processing indirectly have involved the comparison of solid versus liquid forms of food, variations in viscosity or texture, or flavor intensities. The more direct influence of chewing on appetite ratings and food intake has been studied by varying the number of chews of a target food, and examining chewing gum interventions (Hogenkamp & Schiöth, 2013; Miquel-Kergoat, Azais-Braesco, Burton-Freeman, & Hetherington, 2015; Robinson et al., 2014). However, it is recognized that altering chewing in this way also varies oral residence time, eating rate, muscle fatigue and other oral processing attributes. Therefore, the effects of chewing in isolation is rarely studied due to the interrelated nature of these variables.

Lubrication is an important aspect of oral processing in addition to chewing *per se* (Laguna & Sarkar, 2017; Laguna, Farrell, Bryant, Morina, & Sarkar, 2017; Stokes, Boehm, & Baier, 2013). In-mouth lubrication may depend on the type of food consumed, its interactions with saliva and with the oral surfaces (e.g. tongue, teeth, oral palate). The mechanical properties of food can be evaluated using rheological measurements, such as viscosity, small and large deformation rheology. However, rheological measurements do not account for changes that occur in the food during the later stages of oral processing, such as the incorporation of saliva. Furthermore, the rheology of food during oral processing is not static; it is a highly dynamic process and the textural properties change continuously when the food is exposed to the oral cavity and becomes largely tribology-dominant, i.e. lubrication or friction dependent (Stokes et al., 2013). To that end, the lubricating effects arising from the incorporation of saliva can be measured using tribological measurements (Laguna & Sarkar, 2017), a technique introduced relatively recently in food science. Although oral lubrication is an integral part of oral processing, to date this has not been reviewed systematically with reference to satiety.

The main aim of this comprehensive systematic review and meta-analysis was to understand the impact of oral processing, including both chewing and lubrication, on appetite and food intake. It was hypothesized that the enhancement of both chewing and lubrication during oral processing will affect appetite sensations, and reduce food intake. The main dependent variables included were: 1) subjective ratings of hunger and desire to eat as markers of appetite and readiness to eat, and 2) objective measures of energy intake following manipulation of food as a marker of satiation and meal termination. This review aimed to provide insights into potential oral processing manipulation strategies that could ultimately be applied to design foods offering enhanced satisfaction and satiety (Hetherington et al., 2013).

2. Materials and methods

The 2009 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines were used for reporting this systematic review. The search strategy and inclusion criteria were specified in advance and documented in a protocol. This protocol was registered with the International prospective register of systematic reviews PROSPERO, registration number: CRD42016034019.

2.1. Search strategy

A systematic review attempts to collate all empirical evidence that fits pre-specified eligibility criteria to answer a particular research question. The research question of this systematic review was formulated using PICOS (Population, Intervention, Comparison, Outcome, and Setting). The population was defined as healthy people with a healthy oral status that would not interfere with normal chewing and/or oral lubrication. The intervention was considered to be any manipulation directly or indirectly affecting oral processing characteristics, such as eating rate, oral residence time and number of chews, and where the comparison would involve two extreme conditions (see Table 1). For the outcomes, measures related to subjective appetite (hunger, desire to eat) and/or objectively measured food intake, as a consequence of manipulating oral processing, were included. The setting mostly involved a laboratory environment, but other settings were not excluded.

A comprehensive literature search was conducted using six different online databases, including Cochrane Library, OVID Medline, PubMed, OVID Food Science and Technology Abstracts (FSTA), Web of Science (Thomson Reuters) and Scopus (Elsevier). The last search was run on 12 May 2017. Additional studies were identified using the reference lists of the articles found in the search. Only articles published in English were included in this systematic review and no time limit was set. A broad range of search terms were used to increase the chance of locating all relevant literature. Three combined searches were performed in the six selected databases, linking chewing to satiety, lubrication to satiety and tribological measurements to satiety (this is related to lubrication, but extra search key words were added at a later stage). The search terms related to chewing were: [“oral processing” OR chewing OR mastication OR “structural breakdown” OR “food breakdown” OR “food destruction” OR “chewing cycle”]. The lubrication related search terms were: [“oral processing” OR “oral behavio*r” OR lubrication OR saliva OR “artificial saliva” OR “oral coating” OR “oral exposure” OR tongue]. For satiety the following search terms were used: [satiety OR satiation OR “expected satiety” OR “food intake” OR appetite OR hunger OR fullness OR “sensory specific satiety” OR “energy intake” OR “food behavio*r” OR “eating behavio*r”]. The selected key words for the added tribological variable were: [tribology OR tribometer OR thin-film rheology OR soft tribology OR tribol*].

The search in Scopus was limited to publications where the search terms appear in the title, abstract or keywords. No additional limitations were set for the other databases. The search strategy was validated by checking that a number of pre-selected relevant articles were indeed retrieved in at least one of the databases. The pre-selection was made during the orientation phase of literature research, focusing on more general articles based on the research topic, as well as articles found in previous related systematic review by Miquel-Kergoat et al. (2015). The citations of all found articles were exported to the reference software Endnote X7 for further processing.

2.2. Study selection

Only original research reports of human studies were included in this systematic review. The study selection phase was executed by first author EK. A summary of the selection procedure (PRISMA four-phase flow diagram) is given in Fig. 1. The initial 12161 identified articles were reduced to 5825 after duplicates were removed. The remaining articles were screened for relevance based on their title. An additional 5505 studies were excluded based on the PICOS criteria. Research reports involving animal studies (2043), or medical studies on patients with certain diseases or disorders, studies with children, the elderly or participants of whom it was suspected that normal chewing was hindered (1762) were excluded. Additionally, articles not addressing the topic of interest were excluded (5464), as well as studies published in any other language than English (458). Some articles were excluded for multiple reasons, therefore the total number of articles is lower than the sum.

The remaining 320 articles were screened for their abstract, resulting in the exclusion of an additional 241 articles (219 based on their topic, 17 were review papers without original data and 12 were meeting and conference abstracts, as well as posters presentation abstracts, and one was a data-set). The remaining number for the next screening step was n = 100, including an additional 21 articles that were identified through supplementary approaches.

Table 1
Oral processing parameters as compared across studies.

Parameter[a]	Comparison factors	
Bite size (5–15g)	Large	Small
Eating rate	Fast	Slow
Number of chews (10–40 chews)	Low	High
Oral residence time (3–30s)	Short	Long
Texture	Liquid (soft foods)	Semi-solid (hard foods)
Texture complexity	Low	High
Chewing gum	No gum	Gum

[a] In brackets: the lowest and highest values of the different oral processing parameters that were used in the different studies. For instance in the study by Cassady et al., 2009, the lowest number of chews was 10, whereas the lowest number of chews by Li et al., 2011 was 15 number of chews (for both the highest number of chews was 40 per mouthful).

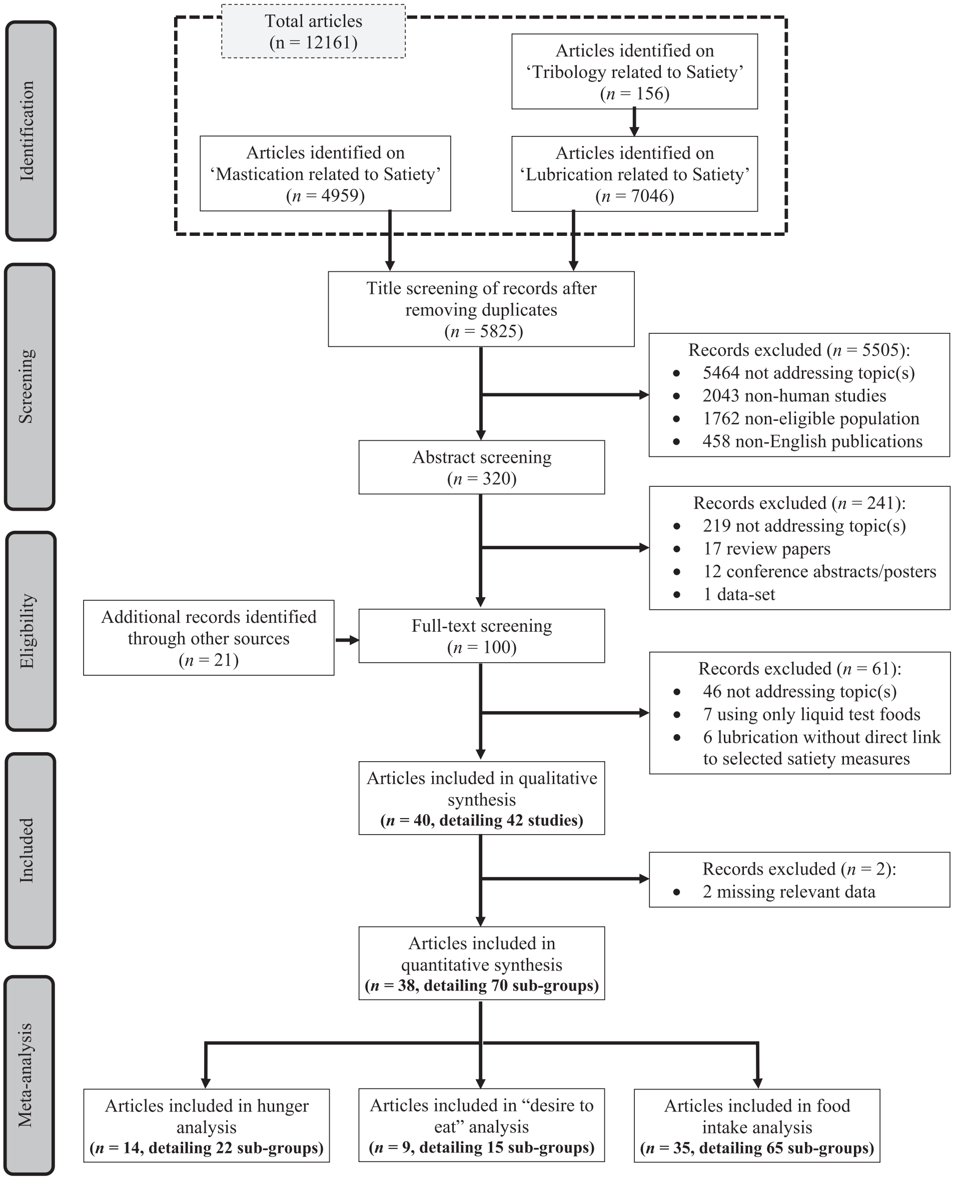

Fig. 1. PRISMA flow-chart of the study selection procedure.

For example, the PRISMA statement for reporting systematic reviews (item 7 https://doi.org/10.1136/bmj.b2700) advocates hand searches of the reference lists from screened articles so that relevant papers are not omitted. Finally, after assessing the full-text of these articles, another 61 articles were excluded for one or more reasons. Articles not addressing the topic of interest or studies aiming at validating new devices or methods (n = 46), articles where the two extreme oral processing characteristics were achieved by comparing two liquid products of for example differing viscosity (n = 7) and studies focusing on lubrication related parameters without direct measures of satiety/satiation (n = 6) were eliminated, leading to a set of 40 articles. Two of those articles reported two independent studies (de Wijk, Zijlstra, Mars, de Graaf, & Prinz, 2008; Zijlstra, Mars, de Wijk, Westerterp-Plantenga, & de Graaf, 2008), bringing the total number of studies for qualitative synthesis to 42.

The quality assessment tool developed and validated by Moore (2012) was used to assess the quality of the included studies. Additionally, these 42 studies were critically appraised for risk of bias at both the study level and outcome levels. The quality and accuracy of a sample (~35%) of the extracted data was checked by authors MH and AS.

2.3. *Study characteristics*

Relevant information, such as study design, participant age, body mass index (BMI) status and gender ratio, as well as study outcomes on appetite ratings and food intake measures, was extracted from the 42 included studies. The key study characteristics are given in Table 2. In addition, means and standard deviations of the two most extreme outcome measures were extracted for the meta-analysis by author EK, as well as their statistical significance (p-values). The corresponding authors of more recent articles, where the values of interest were measured but not actually reported, were contacted with a data request. In the case of 9 articles (10 studies) data was received and incorporated into the current systematic research review (Cassady, Hollis, Fulford, Considine, & Mattes, 2009; Higgs & Jones, 2013; Hogenkamp,

Table 2
Characteristics of studies included in the systematic review involving oral processing manipulations by food.[a]

Reference	Participants			Study information			Outcomes			
	n	Gender (M/F)	BMI groups	Study design	Test food	Test procedure	Appetite method	Effect appetite	Food intake method	Effect food intake
Andrade, Greene, and Melanson (2008)	30	0/30	UW, NW, OW and OB	Randomized, 2-arm, within subjects design	Pasta meal	*Ad libitum* lunch with fast/big bite/no pauses and slow/small bite/chew 20-30 times/pauses condition	VAS	No difference in appetite ratings	Weighing	Yes, under slow eating condition weight and energy intake ↓ compared to fast eating
Bolhuis, Lakemond, de Wijk, Luning, and de Graaf (2011)	55	55/0	NW	Randomized, 6-arm, cross-over design	Tomato soup	Three conditions (2s or 3s oral exposure each 5 or 15s, respectively, or free bite size) for two salt concentrations	VAS	No difference in appetite ratings	Weighing	Yes, intake was ↑ in short oral exposure condition compared to long (34%)
Bolhuis, et al. (2014)	50	11/39	NW	Randomized, 2-arm, cross-over study, within subjects	Hamburger/ rice salad	*Ad libitum* lunch of hard or soft foods, followed by *ad libitum* dinner to test if energy intake was compensated	VAS	No difference in appetite ratings	Weighing	Yes, ↓ intake of hard foods, ↓ energy intake and ↓ eating rate compared to soft foods
Cassady, Hollis, Fulford, Considine, and Mattes (2009)	13	8/5	NW	Randomized, 3-arm, cross-over design, within subjects (no control group, ie 0g almonds)	Almonds	55g almonds (11x5g portions) chewed for 10, 25 or 40 times	VAS	Yes, ↓ hunger with 40 chews than with 25 chews (no diff. with 10 chews)		NA
Ferriday, et al. (2016)[b], Product A and B	24	12/12	NW	Counterbalanced, randomized, 4-arm, cross-over design, within subjects, sample size power calculation	Beef stew with dumplings/ fish, chips and peas	Two fixed test meals with maximized differences in oral processing, followed by *ad libitum* same meal or dessert, and 1h later *ad libitum* snack intake	VAS	Yes, ↑ fullness after eating slow meal than after fast meal	Weighing	Yes, ↓ food intake after slow meal than after fast meal
Forde, Kuijk, Thaler, de Graaf, and Martin (2013)	15	5/10	NW	Full cross-over design, within subjects, randomized within test days, sample size power calculation	35 different food items	50g portions of 35 different food items, across 5 consecutive days, images of 200 g portions for expected satiety assessment (separate descriptive sensory analysis panel, n= 11)	VAS	Yes, ↓ hunger with increased chewing and longer oral exposure time and smaller bite size		NA
Hetherington and Boyland (2007)	60	20/40	UW, NW and OB	Repeated measures, counter-balanced (Latin-square), within subjects design	Sweet or salty snack	Fixed lunch, followed by 4 conditions (no gum sweet snack; no gum salty snack; gum sweet snack; gum salty snack), with gum chewed at 3 time points after lunch and ad libitum intake measured 3h later	VAS	Yes, ↓ hunger and ↑ fullness in chewing gum condition for sweet and savory snacks, with ↓ desire to eat sweet snacks but not savory snacks	Weighing	Yes, ↓ snack intake in chewing gum condition for sweet and savory snacks
Hetherington and Regan (2011)	60	7/53	NW, OW and OB	Repeated measures, counter-balanced, within subjects design	Sweet or salty snack	Restrained eaters: given a fixed lunch, followed by 4 conditions (no gum sweet snack; no gum salty snack; gum sweet snack; gum salty	VAS	Yes, ↓ hunger, desire to eat and ↑ fullness in chewing gum condition at 2 and 3h after lunch	Weighing	Yes, ↓ snack intake in chewing gum condition

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Table 2 (*continued*)

Reference	Participants			Study information			Outcomes			
	n	Gender (M/F)	BMI groups	Study design	Test food	Test procedure	Appetite method	Effect appetite	Food intake method	Effect food intake
						snack), with gum chewed at 4 time points after lunch and ad libitum intake measured 3h later				
Higgs and Jones (2013)	41	7/34	NW	Three groups, between subjects design	Sandwich	Fixed lunch with 3 conditions (habitual chewing n=13; 10s pauses between each mouthful n=14; 30s chewing before swallowing n=14) and its influence on *ad libitum* snack intake 2h later	VAS	No difference in appetite ratings	Weighing	Yes, ↓ snack intake in 30s chewing condition
Hogenkamp, Mars, Stafleu, and de Graaf (2010)	105	46/59	NW	Randomized, 3-arm, between subjects design	Yoghurts	*Ad libitum* yoghurt presented in three groups (liquid-yoghurt/straw n=34, liquid-yoghurt/spoon n=36 and yoghurt-pudding/spoon n=35)	VAS	No difference in appetite ratings	Weighing	Yes, intake on first exposure ↑ for liquid/straw compared to semi-solid/spoon
Hogenkamp, Mars, Stafleu, and de Graaf (2012)	53	12/41	NW	Randomized, 2-arm, cross-over, within subjects design, sample size power calculation	Milk-based custards	*Ad libitum* intake on day 1 and 5, and fixed amount on day 2, 3, and 4 of low vs high expected satiety samples	VAS	No difference between *ad libitum* liquid and solid	Weighing	Yes, liquid product intake ↑ than semi-solid
Hogenkamp, Stafleu, Mars, and de Graaf (2012)	27	9/18	NW	Randomized, 4-arm, cross-over, within subjects design	Novel gelatin products	Fixed product conditions (liquid/semi-solid and low/high energy density) eaten with 3 *ad libitum* main meals a day for three days	10-point categorical scale	Yes, ↑ hunger directly after liquid compared to semi-solid food	Weighing	No difference in intake between liquid and semi-solid preload condition
Julis and Mattes (2007)	47	29/18	OW and OB	Randomized, 3-arm, within subjects design	Free	Fixed lunch 3 conditions (no chewing gum, fixed time gum chewing and gum chewing after first hunger occurrence)	VAS	No difference in appetite ratings	Questionnaire	No difference in snack intake between chewing gum conditions
Komai, et al. (2016)[c]	10	0/10	NW	Randomized, 2-arm, within subjects design	Hamburger, rice and soup	Fixed solid meal with 30 CPM or pureed meal without chewing (0 CPM)	VAS	No difference in appetite ratings		NA
Labouré, van Wymelbeke, Fantino, and Nicolaidis (2002), Product A and B	12	12/0	NW	Randomized, 5-arm, within subjects design	Soups and rusks	Fixed lunch sessions with five products with different textures, followed by an *ad libitum* dinner	VAS	No difference in appetite ratings	Dinner energy and macro-nutrient content	No difference in energy intake at dinner
Larsen, Tang, Ferguson, and James (2016)	26	m/f	NW	Randomized, 2-arm, cross-over, within subjects design	Gelatin-agar gels	Fixed preload of high or low complexity model foods, followed by a	VAS	No difference in appetite ratings	Weighing	Yes, ↓ intake after high complex food compared to low complex food

						two-course *ad libitum* meal				
Lasschuijt, et al. (2017)	58	14/44	NW	Randomized, 4-arm, cross-over, within subjects design, samples size power calculation	κ-carrageenan /locust bean gum gels	*Ad libitum* portion of model foods varying in hardness and sweetness	VAS	No difference in appetite ratings	Weighing	Yes, ↓ intake after hard compared to soft model foods
Lavin, French, Ruxton, and Read (2002)	20	10/10	NW and OW	Four-arm, within subjects design, randomization unclear	Sucrose containing drink/jelly/ pastilles and water	Four preloads (consumed with varying oral durations) with *ad libitum* meal served immediately after preload	VAS	No difference in appetite ratings	Weighing	Yes, energy intake ↓ after pastilles compared to water and the sweet drink
Li, et al. (2011)[,d]	30	30/0	NW + OB	Randomized, 2-arm, within subjects design	Pork pie	*Ad libitum* habitual breakfast with 2 conditions (15 chews or 40 chews, found to be lowest and highest possible chews/bite)	VAS	No difference in appetite ratings	Weighing	Yes, after 40 chews energy intake ↓ than after 15 chews
Martens, Lemmens, Born, and Westerterp-Plantenga (2011)	10	10/0	NW	Randomized, 2-arm, cross-over, within subjects design, sample size power calculation	Chicken breast	Fixed lunch of whole or blended chicken breast (soup)	VAS	No difference in appetite ratings		NA
Martin, et al. (2007)	48	22/0	OW and OB	Randomized, 3-arm, between subjects design, sample size power calculation	Chicken	Baseline meal (normal eating rate), reduced-rate meal (by 50%), combined-rate meal (50% slower during second half of meal)	VAS	No difference in appetite ratings	Weighing	No, food intake did not differ between conditions
Mattes and Considine (2013)	60	30/30	NW + OB	Randomized, 3-arm, cross-over, within subjects design	Pasta meal	Three treatments (no gum, soft or hard gum) chewed at 1 chew/s for 15 min while sipping grape juice through a straw, followed by a 6 hour blood collection and ad libitum lunch and free dinner at home	VAS	No difference in appetite ratings	Weighing + Food record	No difference in energy intake in any of the meals during the test day, however, trend to reduce energy intake in lean participants and increase energy intake in obese participants
McCrickerd, Lim, Leong, Chia, and Forde (2017)[,e]	61	30/31	NW	Counterbalanced, randomized, 4-arm, between subjects design, sample size power calculation	Rice based porridge	*Ad libitum* intake at breakfast of thin and thick porridge with low and high energy density	VAS	No difference in appetite ratings	Weighing	Yes, ↓ intake of thick compared to thin porridge
Mourao, Bressan, Campbell, and Mattes (2007), Product A, B and C	40	20/20?	NW and OB	Randomized, 6-arm, cross-over, between subjects design (in sub-groups within subjects design)	Milk/cheese, Watermelon juice/fruit and Coconut milk/ coconut meat	*Ad libitum* lunch and fixed amount of water, liquid or solid test food with either high carbohydrate, high protein or high fat content	VAS	No difference in appetite ratings between products or BMI status	Weighing	Yes, for all three foods daily intake was ↑ in liquid condition compared to solid foods
Park, et al. (2016)	25	0/25	NW + OB	Randomized, 2-arm, cross-over, within subjects design	Sweet or salty snack	Fixed lunch, followed by 4 conditions (no gum sweet snack; no gum salty snack; gum sweet snack; gum salty snack), with gum chewed at 3 time points after lunch and ad	VAS	Yes, chewing gum ↓ hunger over time compared to not chewing gum	Weighing	No difference in snack intake between chewing gum conditions

(*continued on next page*)

Table 2 (*continued*)

Reference	Participants			Study information			Outcomes			
	n	Gender (M/F)	BMI groups	Study design	Test food	Test procedure	Appetite method	Effect appetite	Food intake method	Effect food intake
						libitum intake measured 3h later				
Smit, Kemsley, Tapp, and Henry (2011)	11	4/7	NW and OB	Counterbalanced, randomized (for last 2 treatments), within subjects design	Pasta meal	Pilot study with 3 treatments (*ad libitum* chewing, 10 or 35 chews per mouthful: CPM)	VAS	No difference in appetite ratings	Weighing	Yes, after 35 CPM food intake ↓ than after 10 CPM
Spiegel, Kaplan, Tomassini, and Stellar (1993), Product A and B	18	0/18	NW and OB	Counterbalanced for bite size, randomized, alternating products between sessions, within subjects design	Sandwich rolls and bagels	*Ad libitum* lunch with food varying in bite size (sandwiches 5, 10 and 15g; bagels 6 or 12g) tested on separate days	VAS	No difference in appetite ratings due to bite size	Weighing	No difference in meal size due to different bite sizes in either products even though the food texture was very different and was eaten at very different ingestion rates (g/min)
Swoboda and Temple (2013)[f]	44	21/23	OW	Randomized, within subjects design (with different subjects for part 1 and 2)	Fruit, sweet or savory snack	Two separate studies: one-day acute effect of chewing gum and effect of chewing gum before each meal for a week	VAS	Yes, chewing either mint or fruit gum ↓ hunger compared to no gum	Weighing	Yes, chewing mint-flavored gum ↓ healthy food intake compared to no gum (however no effect on snack food or total energy intake, nor with fruit gum)
Tang, Larsen, Ferguson, and James (2016)	38	22/16	NW	Single-blind, randomized, 3-arm, cross-over, within subjects design	Gelatin-Agar gels	Fixed preload of high, medium or low complexity model foods, followed by 2 *ad libitum* meal courses	VAS	No difference in appetite ratings	Weighing	Yes, ↓ intake after high complex food compared to low and medium complex food
Weijzen, Liem, Zandstra, and de Graaf (2008)	59	5/54	NW and OW	Randomized, 4-arm cross-over, within subjects design	Biscuits with chocolate/ hazelnut cream filling	Either morning or afternoon *ad libitum* snack intake with snacks varying in size and weight, as well as usual or extra attention paid during consumption	5-point categorical scale	Not reported	Weighing	Yes, snack intake of nibbles ↓ than of bars
de Wijk, Zijlstra, Mars, de Graaf, and Prinz (2008), Study 1	9	4/5	NW and OW	Counterbalanced, randomized, 2-arm, within subjects design (different subjects between Study A and Study B)	Chocolate dairy products	*Ad libitum* intake by straw with fixed eating rate and fixed meal duration (20s intervals over 15min = 45 bites of *ad lib* bite size)	10-point categorical scale	No difference in appetite ratings between liquid and semi-solid foods	Weighing	Yes, semi-solid food intake ↓ than liquid food intake
de Wijk, et al. (2008), Study 2	10	6/4	NW and OW	Counterbalanced, randomized, 3-arm, within subjects design (different subjects between Study A and Study B)	Chocolate dairy products	*Ad libitum* intake of 45 bites by peristaltic pump with varying oral processing time (5 or 9s for semi-solid only) and with eliminated bite effort (*ad lib* bite size)	10-point categorical scale	No difference in appetite ratings between liquid and semi-solid foods	Weighing	No difference in energy intake between liquid and semi-solid food, nor due to oral processing time for semi-solid food
Zandian, Ioakimidis, Bergh, Brodin, and Södersten (2009)	47	0/47	NW	Two groups (decelerated and linear eating rate), within subjects design	Rice meal	Increased eating rate (40% more food in same amount of time) and decreased eating rate (30% less food in same time)	VAS	No difference in appetite ratings	Mandometer	Yes, changing someone's habitual eating rate affected food intake
Zhang, Leidy, and Vardhanabhuti (2015)	12	m/f	NW and OW	Randomized, 5-arm, cross-over, within subjects design, sample size power calculation	Protein snacks	Protein beverages at pH 3 or pH 7, or acid or heated treated gels compared to a water	VAS	No difference in appetite ratings	Weighing	No difference in food intake between protein snacks

						control sample, followed by *ad libitum* lunch				
Zhu and Hollis (2014)	47	24/23	NW, OW and OB	Randomized, 3-arm, cross-over, within subjects design, sample size power calculation	Pizza rolls	*Ad libitum* lunch (no beverage) with predetermined average number of chewing cycles used as baseline for the three treatments (100, 150 and 200%)	VAS	No difference in appetite ratings for treatment or BMI even after a 60 min period	Weighing	Yes, food intake ↓ for 200% chews compared to 100% baseline number of chews
Zhu, Hsu, and Hollis (2013)	21	21/0	NW and OW	Randomized, 2-arm, within subjects design, sample size power calculation	Pasta meal	Fixed pizza meal with 2 chewing conditions (15 and 40 chews), followed by *ad libitum* pasta meal 3h later	VAS	Yes, hunger after 40 chews ↓ compared to 15 chews (however fullness not different)	Weighing	No difference in food intake at lunch meal 3h after chewing intervention
Zijlstra, et al. (2011)	54	12/42	NW + OB	Randomized, cross-over, within subjects design	Rice meal and yoghurt	*Ad libitum* lunch, two sessions of 45 min with a neutrally and highly liked product	VAS	No, satiety ratings for both products were similar, while significantly more calories were consumed with yoghurt	Weighing over time	Yes, ↑ *ad libitum* intake for yoghurt compared to rice
Zijlstra, Mars, Stafleu, and de Graaf (2010), Product A, B and C	106	45/61	NW	Randomized, 6-arm, cross-over, within subjects design (with 7th session to measure eating rate)	Luncheon meat, vegetarian meat replacer and chewy candy	*Ad libitum* snack intake while watching 90 min movie (with two breaks of 15 min in between) receiving 3 x 400g) of three different product types with different levels of hardness	VAS	No difference in appetite ratings between hard and soft versions of all food products	Weighing	No difference in intake between hard and soft version of all food products
Zijlstra, Mars, de Wijk, Westerterp-Plantenga, and de Graaf (2008), Study 1	108	36/72	NW	Randomized, 3-arm, cross-over, within subjects design (different subjects between study 1 and 2)	Chocolate dairy products	*Ad libitum* intake while watching 90 min movie (with two breaks of 15 min in between) receiving 3 x 1500g portions	10-point categorical scale	No difference in appetite ratings between liquid, semi-liquid and semi-solid foods	Weighing	Yes, semi-solid food intake ↓ than liquid food intake
Zijlstra, et al. (2008), Study 2	49	14/35	NW	Randomized, 6-arm, cross-over, within subjects design (different subjects between study 1 and 2)	Chocolate dairy products	*Ad libitum* snack intake under 3 conditions (free eating rate with effort, free eating rate without effort and fixed eating rate without effort at 10s intervals)	10-point categorical scale	No difference in appetite ratings between liquid and semi-solid foods	Weighing	Yes, controlling eating rate and effort had an effect on food intake (for both products, no difference between products). No effect of effort alone (but semi-solid intake ↓ compared to liquid food intake)
Zijlstra, Mars, et al. (2009)	32	12/20	NW	Randomized, 2-arm, cross-over, within subjects design	Chocolate dairy products	*Ad libitum* snack intake after fixed intake of liquids and semi-solids as breakfast time	10-point categorical scale	No difference in appetite ratings between liquid and semi-solid foods	Weighing	No difference in chocolate cake intake after consumption of a liquid or semi-solid product
Zijlstra, de Wijk, Mars, Stafleu, and de Graaf (2009), Condition 1, 2 and 3	22	8/14	NW	Randomized, 7-arm, cross-over, within subjects design	Chocolate dairy product	Control vs different bite size (free, 5 or 15g) and oral processing time (3 or 9s) for at least 30 min	10-point categorical scale	Yes, significant effect of condition on hunger after intake	Weighing	Yes, ↓ intake for 9s oral processing time than for 3s Yes, ↓ intake for 5g bite size than for 15g

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[a] CPM: Chews Per Mouthful, NW: Normal Weight, OB: Obese: OW: Over Weight, UW: Under Weight, VAS: Visual Analogue Scale.
[b] Two studies were reported, only Study 2 was included in this review.
[c] Two studies were reported, only Study 2 was included in this review.
[d] Two studies were reported, only Study 2 was included in this review.
[e] Two studies were reported, only Study 1 was included in this review.
[f] Two studies were reported, only Study 1 was included in this review.

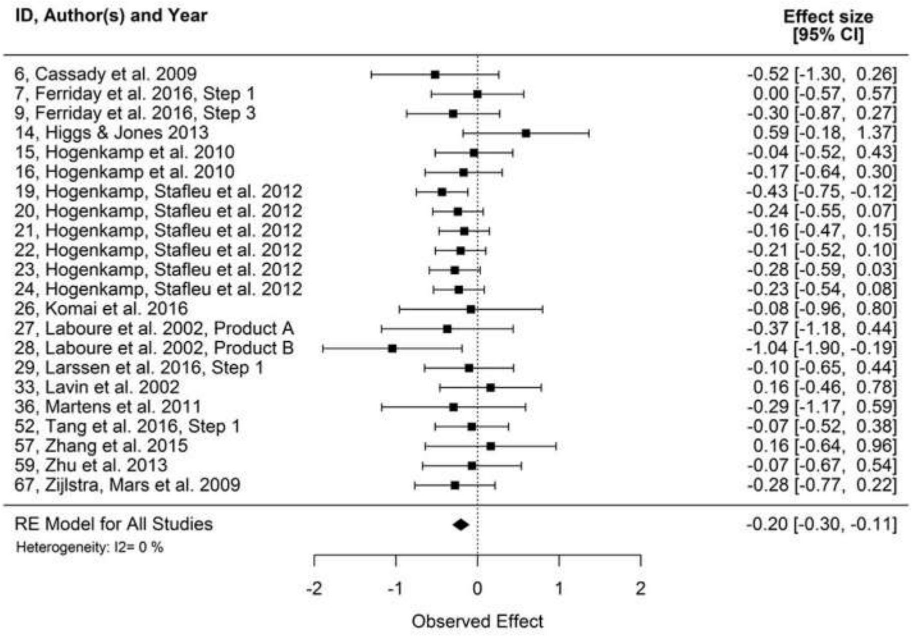

Fig. 2. Forest plot of oral processing effects on the SMD of hunger ratings with corresponding 95% CI. The pooled estimates were obtained using RE modeling. The I^2 value is a measure of the approximate proportion of total variability in point estimates that can be attributed to heterogeneity.

Mars, Stafleu, & de Graaf, 2010, 2012; Hogenkamp, Stafleu, Mars, & de Graaf, 2012; Smit, Kemsley, Tapp, & Henry, 2011; Zijlstra, Mars, Stafleu, & de Graaf, 2010; Zijlstra et al., 2008, Study and 2; Zijlstra, de Wijk, Mars, Stafleu, & de Graaf, 2009) and in the case of the study by Ferriday et al. (2016) additional data was made publicly available online (Bosworth, 2015).

All studies selected for qualitative synthesis were well-controlled experiments, in which participants were randomly assigned to experimental conditions. Of the 42 studies, all but two were laboratory based (Zijlstra et al., 2010; Zijlstra et al., 2008; Study 1) and all but two had a within subjects design (Higgs & Jones, 2013; Hogenkamp et al., 2010). In only 10 of the studies, a power calculation was used to determine the number of participants needed to find a meaningful significant difference (Ferriday et al., 2016; Forde et al., 2013; Hogenkamp, Mars, et al., 2012; Lasschuijt et al., 2017; Martens, Lemmens, Born, & Westerterp-Plantenga, 2011; Martin et al., 2007; McCrickerd, Lim, Leong, Chia, & Forde, 2017; Zhang, Leidy, & Vardhanabhuti, 2015; Zhu & Hollis, 2014; Zhu, Hsu, & Hollis, 2013).

The total number of participants of all 40 studies included in the quantitative synthesis was 1711, arising from studies with samples varying from 9 to 120 participants, and involved mainly young adults (mean 25.1 years). Ideally studies should have an equal ratio of men to women, however for a number of studies more women than men were included, with six studies using more than 70% women (Bolhuis et al., 2014; Hetherington & Regan, 2011; Higgs & Jones, 2013; Hogenkamp, Mars, et al., 2012; Weijzen, Liem, Zandstra, & de Graaf, 2008; Zijlstra et al., 2011). On the other hand, five studies included only males (Bolhuis, Lakemond, de Wijk, Luning, & de Graaf, 2011; Labouré, van Wymelbeke, Fantino, & Nicolaidis, 2002; Li et al., 2011; Martens et al., 2011; Zhu et al., 2013), whereas only four studies included just females (Andrade, Greene, & Melanson, 2008; Komai et al., 2016; Park et al., 2016; Spiegel, Kaplan, Tomassini, & Stellar, 1993). Weight status varied across studies, with 20 studies specifically selecting participants within a healthy BMI range, five studies selecting people from specific weight groups to control for the influence of weight status whereas the remaining 15 studies did not specifically select or control for BMI. From those studies, there were two that also included participants with a BMI higher than 25 (Julis & Mattes, 2007; Martin et al., 2007). In most studies (29 out of 40), participants with any dietary restriction or dramatic weight change were specifically excluded as well as those who reported high levels of dietary restraint (27 out of 40) as assessed by either the Dutch Eating Behavior Questionnaire (DEBQ) (van Strien, Frijters, Bergers, & Defares, 1986) or the Three Factor Eating Questionnaire (TFEQ) (Stunkard & Messick, 1985). None of the studies were double blinded, however in 22 studies the participants were distracted from the true aim through the use of a cover story.

In all studies, the researchers intended to vary only one characteristic of oral processing. However manipulating one characteristic inevitably had an effect on other characteristics (i.e. a higher eating rate might directly shorten the oral residence time). In 16 studies a test food was given with manipulated texture, such as liquid versus semi-solid food, and in two studies a texture complexity component was added. In six studies the number of chews per bite was manipulated, in three studies the oral residence time was directly influenced, and in five studies participants were instructed to eat at a specific chewing rate. Another three studies were included where the bite size was changed, and the final six studies looked at the influence of chewing gum on satiety and food intake during a later meal. For the purpose of the meta-analysis, the minimum and maximum oral processing characteristics were compared to one another (see Table 1). The maximum values were set as the commonly recommended values for reducing food intake and controlling appetite, such as small bites, high number of chews and long oral residence time (Christen & Christen, 1997; Smit et al., 2011). In addition to the 26 studies that directly compared two oral processing parameters, the remaining 14 studies examined other intermediate oral processing conditions that were not considered in this systematic review. However, in the case of the study by Zijlstra, de Wijk, et al. (2009) more separate conditions were considered in the meta-analysis; i.e., conditions comparing different oral residence times after ingestion of free-choice boluses

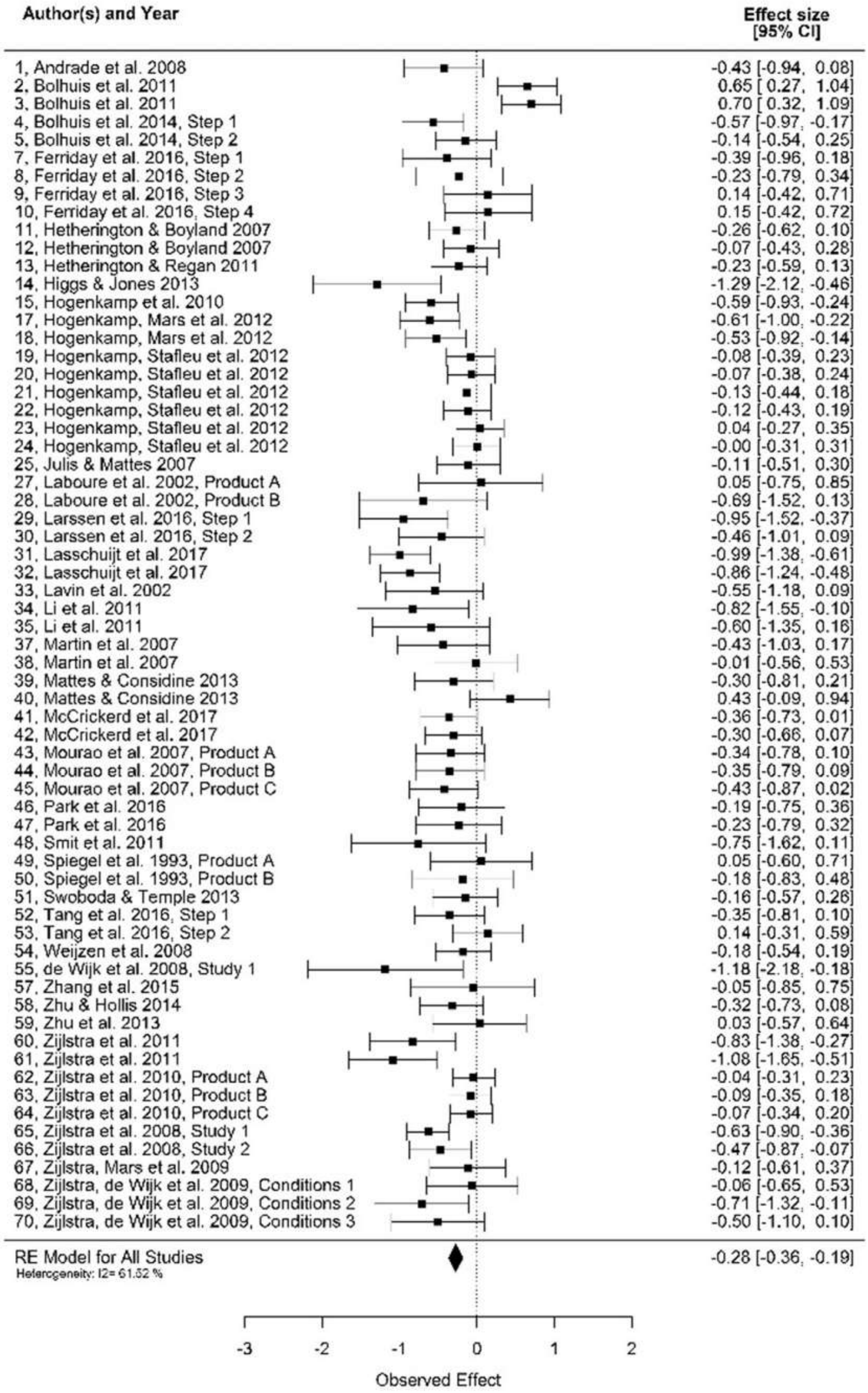

Fig. 3. Forest plot of oral processing effects on the SMD of food intake with corresponding 95% CI. The pooled estimates were obtained using RE modeling.

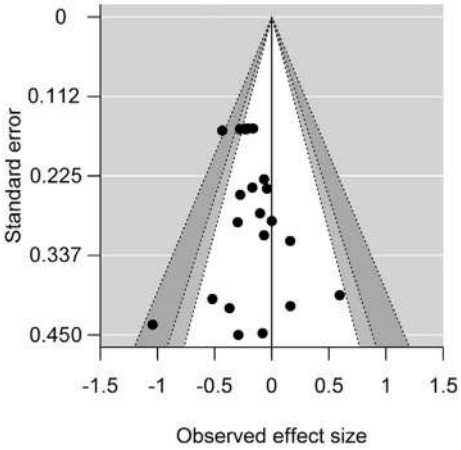

Fig. 4. Funnel plot of oral processing effects on hunger ratings with the different shades corresponding to the 90% CI (white), 95% CI (light grey) and 99% CI (dark grey).

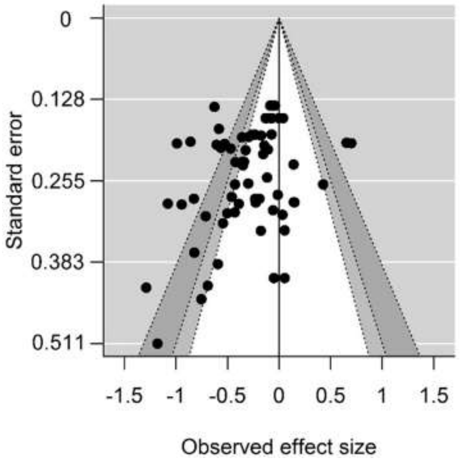

Fig. 5. Funnel plot of oral processing effects on food intake with the different shades corresponding to the 90% CI (white), 95% CI (light grey) and 99% CI (dark grey).

of liquid food (which the authors called “bites”) as well as small and large boluses delivered with a peristaltic pump.

In the second search for papers linking lubrication or tribological parameters of food to satiety measures, a relatively small number of studies were found which had a comparable study design. Only six studies emerged investigating a link between a lubrication parameter and satiety. These papers are discussed separately and were not included in the meta-analysis, since most did not examine any direct satiety measure, or they measured expected satiety.

2.4. Meta-analysis

For the purpose of the meta-analysis, an additional two articles were excluded because appropriate data on a number of outcome measures were missing (Forde et al., 2013; Zandian, Ioakimidis, Bergh, Brodin, & Södersten, 2009). The remaining 38 articles, detailing 40 studies, were further divided in 70 subgroups (See Fig. 1), as some studies provided more than one unique comparison group. Rather than combining these groups (study as unit of analysis), we entered each subgroup separately into the meta-analysis (subgroup within study as unit of analysis). These subgroups included the same experiment repeated with different test foods, indicated by Product A, B etc., such as Labouré et al. Part A studying soups and Part B looking at rusks (Labouré et al., 2002), as well as studies with different participant groups, indicated by Group A, B etc., such as Martin et al. Group A with all males and Group B with all females (Martin et al., 2007). Some subgroups were indicated with Step 1, 2 etc, such as Bolhuis et al. Step 1 for *ad libitum* course one: lunch, and Bolhuis et al. Step 2 for *ad libitum* course 2: dinner (Bolhuis et al., 2014), as well as Part A, B etc. to indicate different subgroups that did not necessarily have an effect on oral processing for example different energy density products or different test days as extra replicates. The participants' characteristics of all individual subgroups can be found in Supplementary Table 1.

The meta-analysis was conducted on three outcome measures: subjective appetite ratings of hunger and desire to eat and objective measures of food intake (see Supplementary Tables 2 and 3). Despite the importance of standardizing hunger levels before the oral processing manipulation, only seven studies provided a standard or preload meal (Bolhuis et al., 2011; Lasschuijt et al., 2017; Mourao, Bressan, Campbell, & Mattes, 2007; Zhang et al., 2015; Zijlstra et al., 2010; Zijlstra et al., 2008; Study 1 and 2). The oral processing intervention consisted of a fixed amount of food or was an *ad libitum* meal where food intake was measured. In some studies *ad libitum* intake was permitted during the oral processing intervention, and in others there was a fixed amount of food consumed. In one study *ad libitum* intake was measured twice, once during the oral processing intervention and again at the test meal (Bolhuis et al., 2014). Appetite ratings were measured at baseline on arrival in the lab and/or directly after the standard meal. Measurements were repeated directly after the oral processing intervention, and in some cases at 30 min or hourly intervals after for a specific period of time.

Appetite ratings were measured on 100 mm Visual Analog Scales (VAS) or categorical rating scales. The 10-point or 5-point scores were converted to a 100 point scale, so appetite ratings could be better compared against each other. When appetite was assessed at multiple time points after the oral processing manipulation, the ratings directly after the end of manipulation were retrieved. To control for differences in appetite levels before the start of the study due to varying fasting states, for example, the change in mean appetite level was computed (raw mean difference, e.g. hunger level after chewing intervention minus the baseline hunger level). Food intake was measured after the chewing manipulation in either weight (g) or energy (kcal or kJ). Where needed, given values were converted to kcal to standardize the measurement units. Mean, standard deviation and sample size for each group were extracted for all papers where they were reported. To account for differences in the measurement scales, the standardized mean difference (SMD) was used to compute the effect size (Borenstein, Hedges, Higgins, & Rothstein, 2009, pp. 21–32). The studies employing a between subjects design were treated as independent studies, whereas the studies employing a within subjects design were considered as dependent studies. For the food intake studies a correlation coefficient of 0.5 was assumed and for the appetite studies a correlation coefficient of 0.2. Both correlation coefficients were based on the few studies where raw data was available to determine the actual correlation coefficients (Cassady et al., 2009; Ferriday et al., 2016; Hetherington & Boyland, 2007; Hogenkamp, Stafleu, et al., 2012; Smit et al., 2011).

Since the studies from our sample used different methodologies, the meta-analysis was performed using a random effects (RE) model. The heterogeneity was assessed with the I^2 statistic as indicator for the percentage of statistically meaningful variability between studies. An I^2 value of 0% means there is no heterogeneity that needs to be explained, values of 25% are considered low, 50% moderate and above 75% is considered high (Higgins, Thompson, Deeks, & Altman, 2003). If heterogeneity between studies was considered high, we tried to explain this further by implementing a mixed effects (ME) model with a number of moderators, such as fasting time, participants' age and BMI status. To investigate risk of publication bias across the studies, funnel plots were produced. A funnel plot is used to visually represent high oral processing effect estimates from individual studies against the standard error of each study. Typically the precision of an estimate increases with the size of the study, with studies with a small sample size distributed towards the bottom of the plot and studies with a larger sample size scattered towards the narrower top of the funnel plot as they are more precise. The different shades of the funnel plot correspond to the 90% confidence interval CI (white), 95% CI (light grey) and 99% CI (dark grey). The free statistical software R® (version 3.3.1) and the metaphor package (version 1.9–9) were used to conduct the meta-analyses (forest plots and funnel plots). The software Comprehensive Meta-Analysis (version 2.2) was used to conduct the sensitivity and group effect analyses, as well as the Egger's tests to assess publication bias (Egger, Davey Smith, Schneider, & Minder, 1997).

3. Results

A total of 40 articles, that included 42 studies, were found suitable for qualitative analysis (see Fig. 1 and Table 2).

3.1. Effect of food oral processing on appetite

Based on the 42 studies that measured appetite ratings, 10 found significant effects on the appetite ratings, such as hunger, fullness and desire to eat. This disparity in the results may be associated with the study methodology employed, such as having a fixed amount of food to chew. For example, Cassady et al. (2009) provided their participants with a fixed amount of almonds to chew for different number of times (10, 25 or 40 chews). They found that a larger number of chews significantly reduced appetite. A fixed amount of food was also given during the manipulation of oral processing in five other studies that found a significant effect on appetite (Ferriday et al., 2016; Forde et al., 2013; Hogenkamp, Stafleu, et al., 2012; Zhu et al., 2013; Zijlstra, de Wijk et al., 2009). When *ad libitum* meals were provided, participants ate until they reached a certain level of fullness, so the change in appetite ratings was similar regardless of the amount consumed or how much energy was ingested. If an excess amount of food is offered in an *ad libitum* meal, the motivation to eat may be stronger than the oral processing manipulation itself.

3.2. Effect of oral processing on food intake

Four studies did not measure *ad libitum* food intake during or after the oral processing intervention (Cassady et al., 2009; Forde et al., 2013; Komai et al., 2016; Martens et al., 2011), and therefore were not considered in this section of the review. Thus, the total number of studies that measured food intake was 38. Food intake was measured either at the same time as the oral processing intervention occurred, e.g. number of chews was manipulated during an *ad libitum* meal (Li et al., 2011), or after the oral processing manipulation, e.g. Zhu et al. (2013).

The effect of oral processing on objective measures of food intake was significant in 26 studies, but no clear patterns were evident. The provision of a fixed meal to standardize hunger before the oral processing intervention was linked to a significant effect in food intake in seven studies (Bolhuis et al., 2011; Hetherington & Boyland, 2007; Hetherington & Regan, 2011; Lasschuijt et al., 2017; Mourao et al., 2007; Zijlstra et al., 2008; Study 1 and 2), which seems to highlight the importance of a standardized meal to ensure a similar level of hunger between participants before the oral processing manipulations.

3.3. Effect of lubrication on appetite and food intake

Six articles were identified that mentioned some links between lubrication and satiety (see Supplementary Table 4). McCrickerd, Chambers, and Yeomans (2014) tested the satiety effects of fruit drinks varying in thickness and creaminess. The viscosity and lubrication profiles of the test drinks showed that the thickened drinks were more viscous and more lubricating, having a lower traction coefficient than the thin drinks. No effect was found on satiety ratings, but they did observe a difference in food intake where female participants self-selected a smaller portion size when the drink's visual sensory characteristics indicated it would be more satiating (McCrickerd et al., 2014). A limitation of this study was that participants were allowed to self-select their own portion size in a glass from a larger amount of the drink in a jug, after assessing the sensory characteristics. The results might have been clearer if the sensory aspects were evaluated by a different panel, and if the panelists were instructed to drink directly from a larger or fixed amount to ensure satiation. A mindful assessment of the drink attending to the sensory features of the drinks before *ad libitum* intake might have influenced the results. Moreover, as also suggested by the authors, the portion size effect might have had a bigger influence on intake than the texture manipulation. It was suggested that the average portion size for men was bigger than the serving glass could hold, but was smaller for women. Therefore the portion size could explain the lack of effect found in male participants, while there was an effect for female participants.

In a study by Morell, Fiszman, Varela, and Hernando (2014) the effect of four different hydrocolloids in milkshakes with similar viscosity during pouring and handling conditions on expected satiety was investigated. They found that the starch granules (mainly in modified starch) swell up and disintegrate in presence of artificial saliva. However, the structural properties of guar gum and λ-carrageenan milkshakes remained more or less intact. In addition, the modified starch milkshake had a higher expected satiety. It was hypothesized that expected satiety was more linked to the initially perceived thickness and creaminess of foods and that the loss of structure in presence of saliva is linked to a melting sensation of the modified starch in the mouth (Morell et al., 2014). However, this melting sensation could be a function of better lubrication, which in this case seems to be related to higher expected satiety, suggesting later stages of oral processing could be just as important to satiety perceptions as the initial stages. In addition, Stribeck analysis of these milkshakes with or without saliva was not performed to confirm whether the milkshakes had significantly different friction coefficients in the mixed regime. In another study by Morell, Hernando, Llorca, and Fiszman (2015) the influence of different proteins and presence of starch in yoghurts was studied in relation to expected satiety. In line with their previous study, it was found that addition of starch, as well as addition of protein, increased expected satiety with whey protein having more potential to increase expected satiety than skimmed milk powder. The breakdown of starch in presence of saliva and linked melting sensation was not found here, as the starch granules were incorporated in the protein network, aggregating upon exposure to artificial saliva (Morell et al., 2015).

In a study by Gavião, Engelen, and van der Bilt (2004) several oral processing characteristics of different food products were determined. Dry Melba toast resulted in a longer oral residence time with more chewing cycles, whereas the addition of margarine reduced the time until swallowing as well as the number of chews.

This was largely attributed to the lubricating effects of butter facilitating bolus formation (Gavião et al., 2004), however no quantitative tribological measurement of the bolus was performed to confirm such findings. Joyner, Pernell, and Daubert (2014) tested the friction behavior of acid milk gels with and without the addition of saliva. The addition of saliva was found to cause a significant change in the frictional behavior of the acid milk gels, with a stronger effect seen in samples containing starch (Joyner et al., 2014). However, in both of these studies no direct link was made with any satiety parameters. Finally, Lett, Norton, and Yeomans (2016) have shown the effects of physicochemical characteristics (e.g. droplet size) of model (emulsions) affecting hunger and food intake. They highlight that the tribological and rheological properties of these emulsions are the same; however, exact coefficients of friction at orally relevant speeds are not mentioned (Lett, Norton, et al., 2016; Lett, Yeomans, Norton, & Norton, 2016). These reports suggests that there is growing interest in lubrication measurements but these have yet to be studied in depth for a potential contribution (if any) to satiety and food intake.

3.4. Meta-analysis

The 38 articles included in the meta-analysis were divided into 70 individual subgroups. The narrative part of this systematic review indicated that for the two appetite ratings (hunger and desire to eat), the different methodology of a fixed or *ad libitum* meal might have significant effects on the study outcomes. The studies were divided into groups where either a fixed amount was used for the oral processing manipulation (Type 1), or where an *ad libitum* amount of food was presented (Type 2). For the meta-analysis on hunger ratings, 14 Type 1 studies including 22 subgroups and 14 Type 2 studies with 22 subgroups reported data. The studies where chewing gum was used to manipulate oral processing, and thus no food was ingested, were not included in the meta-analysis for appetite.

Fig. 2 shows the meta-analysis results of the Type 1 studies. The results confirmed that a higher level of oral processing had a significant effect on reducing hunger ratings (−0.20 effect size, 95% confidence interval CI: −0.30, −0.11, I^2 statistic = 0%). The meta-analysis was also performed with both the Type 1 and Type 2 studies included, and the results remained similar (−0.21 effect size, 95% CI: −0.27, −0.15, $I^2 = 0\%$). The ME model using moderators indicated that the included moderators were unable to better explain the total amount of heterogeneity, as the heterogeneity level was already 0%. Subgroup analysis revealed that the oral processing variables eating rate and texture had a significant effect on hunger ratings, whereas bite size, oral residence time, number of chews and texture complexity on their own did not affect hunger. It is however important to note that few studies were included for the latter variables, where no significant effect was found. For the desire to eat ratings, 9 studies including 15 subgroups reported data. The meta-analysis showed similar results to that of the hunger ratings namely that higher oral processing reduced self-reported desire to eat (−0.21 effect size, 95% CI: −0.31, −0.10, $I^2 = 0\%$, see Supplementary Fig. 1).

Meta-analysis of the food intake data included 35 studies with 65 subgroups. Study 2 by de Wijk et al. (2008) did not provide the standard deviations for food intake and therefore was not included in the meta-analysis. A significant effect of oral processing reducing food intake was found (−0.28 effect size, 95% CI: −0.36, −0.19, $I^2 = 61.52\%$), as can be observed in Fig. 3. This is in line with what we expected, given the large amount of individual studies that found a significant effect. The I^2 value did indicate a moderate level of heterogeneity, however the ME model using moderators did not result in a consistent improvement. Subgroup analysis revealed that there was no significant effect of oral residence time alone on food intake, however there were only two studies that looked specifically at oral residence time. The other oral processing factors all included more than two studies, and all showed a significant effect on reducing food intake. Furthermore, as there are different processes that might affect food intake over time, such as cephalic-phase responses in anticipation of food after eating chewing gum or cognitive processes due to the increased expected satiating power of harder, thicker and chewier food, the meta-analysis outcome was tested when Type 1 studies were excluded. However, when only looking at the studies that measured *ad libitum* food intake at the same time as the oral processing intervention, the outcome was not affected (−0.45 effect size, 95% CI: −0.55, −0.35, $I^2 = 69.06\%$).

Publication bias was assessed using funnel plots and the Egger's regression test. The funnel plot for the hunger ratings (Fig. 4) shows a relatively good distribution over the vertical axis, indicating that studies with different sample sizes were included. However, the majority of the studies clustered towards to the left of the mean, indicating there might be evidence of publication bias. Nevertheless, this visual impression was not supported by the Egger's test (P = 0.17, CI: −1.01, 0.18). The asymmetry in the funnel plot for food intake in Fig. 5 also shows a potential bias in favor of studies that found oral processing had an effect on lowering food intake. This was confirmed by the Eggers's test (P = 0.000, CI: −3.59, −1.25).

4. Discussion

The main aim of this comprehensive systematic review and meta-analysis was to understand the impact of oral processing, including chewing and lubrication, on appetite and food intake. It was hypothesized that enhanced oral processing would affect appetite sensations, and reduce food intake. Oral processing is an important factor in the development of satiation and satiety. The results of this review indicate that self-reported appetite and measured food intake are influenced by manipulating components of oral processing such as eating rate, texture and chewing. Thus, where participants are instructed to use a certain oral processing strategy such as the number of times a food is chewed, this will alter how much is eaten. Where participants are provided with foods which increase oral residence time, and/or slow the rate of eating, this reduced subjective appetite. The analyses demonstrate that increased oral processing appears to promote satiation, although it is difficult to isolate which specific component is directly influencing the outcome. Larsen, Tang, Ferguson, and James (2016) developed a model food where the oral residence time was kept constant while texture complexity was varied. This enabled the study to examine texture complexity controlling for oral exposure time. They found that providing a more complex, orally stimulating first course promoted satiation and reduced food intake at a subsequent second course. Therefore, enhanced oral processing through greater textural complexity, can lead to enhanced satiety.

Few studies have been performed focusing on the effects of oral lubrication on appetite and satiety, even though this is an aspect that is also manipulated when looking at foods with differently designed textures (e.g. soft vs hard). Additionally, it is worth noting that saliva has an important role in the cephalic phase linked to amylase digestion (Giduck, Threatte, & Kare, 1987), however this was not within the scope of the present review and we have only considered the lubrication (tribological) aspects of saliva.

The results of these meta-analyses suggest that varying different components of oral processing taken together, can have a significant influence on reducing hunger ratings and food intake. Overall, from the literature included in this systematic review, it is clear that all studies involved a relatively low number of participants (varying from 9 to 120) and a short-term intervention (only once in most studies). Studies with a larger sample size involving longer well-described replicable interventions (from weeks to months) are needed to understand the impact of oral processing on long-term satiety enhancement and its potential in weight management. In addition, product differences need to be large enough to be detectable by consumers to find a potential influence due to oral processing.

The lack in standardization of study design is a key limitation in this systematic review. Blundell et al. (2010) have advocated that for all studies of satiation and satiety, a framework should be applied to standardize procedures; as was also suggested by the results in this review, by standardization of prior hunger levels using a fixed meal before the oral processing intervention takes place, the actual study effects can be studied more carefully (Blundell et al., 2010). The recommended study procedure for satiation studies includes a standard, fixed meal based on individuals' estimated daily energy needs before oral processing is manipulated. Furthermore, for satiety studies, the satiety quotient, the time until the next eating occasion, should be reported in addition to subjective hunger ratings and how much is eaten at the next eating occasion (Blundell et al., 2010). Thus, conclusions regarding the effects of oral processing on satiety must be made with caution since varying results may be attributable to differences in study design. Moreover, dimensions such as food type, meal occasion, differences between individuals or specific participant groups, such as male/female (Martin et al., 2007) or low/high BMI status (Mattes & Considine, 2013; Zhu & Hollis, 2014), appeared to have an influence on the outcome as well.

A systematic review and meta-analysis by Robinson et al. (2014) studied the effects of the specific oral processing characteristic of eating rate on hunger and energy intake. They concluded that a slower eating rate led to a lower energy intake as compared to a faster eating rate, and that different ways in which eating rate could be manipulated (directly or indirectly) did not alter the outcome. No effect of eating rate on hunger was found directly after the meal or up to 3.5h after the meal, both in the analysis with *ad libitum* studies as well as the fixed studies. The difference with our results on the hunger ratings could be explained by including more oral processing variables, and also many more studies were included (five compared to 22 subgroups in the current review with fixed amounts of foods). Another systematic review by Miquel-Kergoat et al. (2015) compared the outcome measure of hunger ratings and energy intake under different oral processing conditions, with the addition of gut hormones and metabolites. Besides hunger ratings, meta-analyses in the current review focused on food intake and desire to eat data, thereby broadening the scope of the review. Also, the oral processing definition was expanded to include aspects of lubrication and saliva incorporation. Finally, oral processing parameters were grouped together according to the recommended oral processing strategies commonly suggested for better weight management such as slow eating rates, high number of chews and longer oral resident time (Christen & Christen, 1997; Ford et al., 2010; Smit et al., 2011). Moreover, additional data not included in the original publication was requested from authors. Instead of comparing 13 subgroups as was reported by Miquel-Kergoat et al. (2015), the current review included hunger ratings from 22 subgroups. Therefore, the present review allows a more comprehensive and advanced analysis by broadening the scope of the used measures, expanding the search to include lubrication, and performing detailed analysis using raw data from authors.

5. Conclusions

In this study we conducted a comprehensive systematic review to assess different oral processing characteristics on appetite ratings and food intake. In order to address this quantitatively, a meta-analysis was undertaken to test the effect size of self-reported appetite ratings and objectively measured food intake in studies that manipulated oral processing parameters, such as oral residence time, texture, eating rate, chewing and lubrication. The meta-analysis demonstrated that manipulating oral processing through slow eating rates and textural complexity reduced subjective appetite and greater oral processing through strategies such as greater chewing reduced food intake.

Although evidence was found for the effects of oral processing on appetite ratings and food intake, this systematic review identified a clear gap in knowledge on the influence of saliva incorporation and oral lubrication on appetite ratings and food intake. The influence of the lubrication parameters of food (pre and post mixing with saliva) on appetite and food intake remains largely unquantified. Furthermore, the studies involving lubrication did not perform tribological measurements of the food and the bolus to quantify differences in lubrication profiles. Future research should be conducted following the framework outlined by Blundell et al. (2010) and standardize prior hunger before oral processing manipulations, which should be apparent and not subtle. With carefully planned and standardized procedures, the knowledge base on the importance of all aspects of oral processing, including both chewing and lubrication, for satiation and satiety development will be expanded and potential application to weight management can be explored. Such knowledge, together with longer interventions, are needed to underpin the creation of the next generation of foods for weight management and allow the development of coordinated public health strategies to tackle obesity.

Author contributions statement

The authors' responsibilities were as follows — MH and AS: designed the research; EK: developed the search protocol, conducted the systematic review and collected and organized the data for the meta-analysis; EK and CN: prepared the data for meta-analyses; LP: ran the meta-analyses; EK, CN and LP: analyzed and interpreted the meta-analysis results; EK: wrote the manuscript; MH, SM and AS: contributed to revisions of the manuscript; AS and MH: had primary responsibility for final content; and all authors: read, edited and approved the final manuscript.

Conflicts of interest statement

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.appet.2018.01.018.

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