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

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19 **Abstract**

20 Food delivers energy, nutrients and a pleasurable experience. Slow eating and prolonged oro-
21 sensory exposure to food during consumption can enhance the processes that promote satiation.
22 This systematic review and meta-analysis investigated the effects of oral processing on subjective
23 measures of appetite (hunger, desire to eat) and objectively measured food intake. The aim was to
24 investigate the influence of oral processing characteristics, specifically “chewing” and
25 “lubrication”, on “appetite” and “food intake”. A literature search of six databases (Cochrane
26 library, PubMed, Medline, Food Science and Technology Abstracts, Web of Science, Scopus),
27 yielded 12161 articles which were reduced to a set of 40 articles using pre-specified inclusion and
28 exclusion criteria. A further two articles were excluded from the meta-analysis due to missing
29 relevant data. From the remaining 38 papers, detailing 40 unique studies with 70 subgroups, raw
30 data were extracted for meta-analysis (food intake n=65, hunger n=22 and desire to eat ratings
31 n=15) and analyzed using random effects modelling. Oral processing parameters, such as number
32 of chews, eating rate and texture manipulation, appeared to influence food intake markedly but
33 appetite ratings to a lesser extent. Meta-analysis confirmed a significant effect of the direct and
34 indirect aspects of oral processing that were related to chewing on both self-reported hunger (-0.20
35 effect size, 95% confidence interval CI: -0.30, -0.11), and food intake (-0.28 effect size, 95% CI: -
36 0.36, -0.19). Although lubrication is an important aspect of oral processing, few studies on its
37 effects on appetite have been conducted. Future experiments using standardized approaches should
38 provide a clearer understanding of the role of oral processing, including both chewing and
39 lubrication, in promoting satiety.

40 **Keywords: Oral Processing, Satiety, Satiation, Hunger, Food Intake, Lubrication.**

41 **List of non-standard abbreviations**

42 WHO: World Health Organization

43 FSTA: Food Science and Technology Abstracts

44 PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis

45 PICOS: Population, Intervention, Comparison, Outcome, and Setting

46 DEBQ: Dutch Eating Behavior Questionnaire

47 TFEQ: Three Factor Eating Questionnaire

48 VAS: Visual Analogue Scales

49 M/F: Male/Female

50 NA: Not Applicable/Available

51 UW: Underweight, BMI $<18.5 \text{ kg/m}^2$

52 NW: Normal Weight, BMI of $18.5\text{--}24.9 \text{ kg/m}^2$

53 OW: Overweight, BMI of $25\text{--}29.9 \text{ kg/m}^2$

54 OB: Obese, BMI $\geq 30 \text{ kg/m}^2$

55 RE model: Random Effects model

56 ME model: Mixed Effects model

57 DE: Desire to Eat

58 **Introduction**

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

69 While the terms “satiation” and “satiety” are often used synonymously in the literature, they
70 encompass different components of the satiety cascade. Satiation is defined as the processes leading
71 to meal termination, and therefore includes all events taking place during the course of the eating
72 occurrence and controls meal size (Blundell, et al., 2009). On the other hand, satiety is described
73 as the inhibition of further eating as well as the suppression of feelings of hunger (Blundell, et al.,
74 2009; Blundell, et al., 2010). Satiety has an influence on the time between two meals during which
75 hunger, which has been suppressed, then begins to increase until the next eating occurrence.
76 Constructs such as hunger and desire to eat represent approach behaviors indicative of appetite or
77 readiness to eat (Stubbs, et al., 2000). During sham feeding studies in humans, chewing fails to
78 reduce hunger and desire to eat (subjective appetite) but produces sensory specific satiety and
79 decreases food intake (Nolan & Hetherington, 2009). Therefore, in examining the effects of oral
80 processing it is important to attend to behavioural markers of both appetite and satiation.

81 During food consumption, food is processed in the mouth from first bite to swallowing, primarily
82 involving reduction in the particle size driven by “chewing”, and the incorporation of saliva to form
83 a swallowable bolus through “oral lubrication” (Chen, 2009; Chen & Stokes, 2012; Sarkar & Singh,
84 2012; Sarkar, Ye, & Singh, 2017). Depending on the nature of food and its oral interactions, the
85 length or intensity of the oro-sensory exposure (i.e. oral residence time) may vary (Ferriday, et al.,
86 2016; Forde, Kuijk, Thaler, de Graaf, & Martin, 2013; Laguna & Sarkar, 2016; Viskaal-van
87 Dongen, Kok, & de Graaf, 2011). For instance, in previous studies food manipulations to influence
88 oral processing indirectly have involved the comparison of solid versus liquid forms of food,
89 variations in viscosity or texture, or flavor intensities. The more direct influence of chewing on
90 appetite ratings and food intake has been studied by varying the number of chews of a target food,
91 and examining chewing gum interventions (Hogenkamp & Schiöth, 2013; Miquel-Kergoat, Azais-
92 Braesco, Burton-Freeman, & Hetherington, 2015; Robinson, et al., 2014). However, it is recognized
93 that altering chewing in this way also varies oral residence time, eating rate, muscle fatigue and
94 other oral processing attributes. Therefore, the effects of chewing in isolation is rarely studied due
95 to the interrelated nature of these variables.

96 Lubrication is an important aspect of oral processing in addition to chewing per se (Laguna, Farrell,
97 Bryant, Morina, & Sarkar, 2017; Laguna & Sarkar, 2017; Stokes, Boehm, & Baier, 2013). In-mouth
98 lubrication may depend on the type of food consumed, its interactions with saliva and with the oral
99 surfaces (e.g. tongue, teeth, oral palate). The mechanical properties of food can be evaluated using
100 rheological measurements, such as viscosity, small and large deformation rheology. However,
101 rheological measurements do not account for changes that occur in the food during the later stages
102 of oral processing, such as the incorporation of saliva. Furthermore, the rheology of food during
103 oral processing is not static; it is a highly dynamic process and the textural properties change
104 continuously when the food is exposed to the oral cavity and becomes largely tribology-dominant,
105 i.e. lubrication or friction dependent (Stokes, et al., 2013). To that end, the lubricating effects arising
106 from the incorporation of saliva can be measured using tribological measurements (Laguna &

107 Sarkar, 2017), a technique introduced relatively recently in food science. Although oral lubrication
108 is an integral part of oral processing, to date this has not been reviewed systematically with
109 reference to satiety.

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

119 **Materials and methods**

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

125 **Search strategy**

126 A systematic review attempts to collate all empirical evidence that fits pre-specified eligibility
127 criteria to answer a particular research question. The research question of this systematic review
128 was formulated using PICOS (Population, Intervention, Comparison, Outcome, and Setting). The
129 population was defined as healthy people with a healthy oral status that would not interfere with
130 normal chewing and/or oral lubrication. The intervention was considered to be any manipulation

131 directly or indirectly affecting oral processing characteristics, such as eating rate, oral residence
132 time and number of chews, and where the comparison would involve two extreme conditions (see
133 **Table 1**). For the outcomes, measures related to subjective appetite (hunger, desire to eat) and/or
134 objectively measured food intake, as a consequence of manipulating oral processing, were included.
135 The setting mostly involved a laboratory environment, but other settings were not excluded.

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

153 The search in Scopus was limited to publications where the search terms appear in the title, abstract
154 or keywords. No additional limitations were set for the other databases. The search strategy was
155 validated by checking that a number of pre-selected relevant articles were indeed retrieved in at
156 least one of the databases. The pre-selection was made during the orientation phase of literature

157 research, focusing on more general articles based on the research topic, as well as articles found in
158 previous related systematic review by Miquel-Kergoat, et al. (2015). The citations of all found
159 articles were exported to the reference software Endnote X7 for further processing.

160 **Study selection**

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

172 The remaining 320 articles were screened for their abstract, resulting in the exclusion of an
173 additional 241 articles (219 based on their topic, 17 were review papers without original data and
174 12 were meeting and conference abstracts, as well as posters presentation abstracts, and one was a
175 data-set). The remaining number for the next screening step was n=100, including an additional 21
176 articles that were identified through supplementary approaches. For example, the PRISMA
177 statement for reporting systematic reviews (item 7 <https://doi.org/10.1136/bmj.b2700>) advocates
178 hand searches of the reference lists from screened articles so that relevant papers are not omitted.
179 Finally, after assessing the full-text of these articles, another 61 articles were excluded for one or
180 more reasons. Articles not addressing the topic of interest or studies aiming at validating new
181 devices or methods (n=46), articles where the two extreme oral processing characteristics were

182 achieved by comparing two liquid products of for example differing viscosity (n=7) and studies
183 focusing on lubrication related parameters without direct measures of satiety/satiation (n=6) were
184 eliminated, leading to a set of 40 articles. Two of those articles reported two independent studies
185 (de Wijk, Zijlstra, Mars, de Graaf, & Prinz, 2008; Zijlstra, Mars, de Wijk, Westerterp-Plantenga, &
186 de Graaf, 2008), bringing the total number of studies for qualitative synthesis to 42.

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

191 **Study characteristics**

192 Relevant information, such as study design, participant age, body mass index (BMI) status and
193 gender ratio, as well as study outcomes on appetite ratings and food intake measures, was extracted
194 from the 42 included studies. The key study characteristics are given in **Table 2**. In addition, means
195 and standard deviations of the two most extreme outcome measures were extracted for the meta-
196 analysis by author EK, as well as their statistical significance (p-values). The corresponding authors
197 of more recent articles, where the values of interest were measured but not actually reported, were
198 contacted with a data request. In the case of 9 articles (10 studies) data was received and
199 incorporated into the current systematic research review (Cassady, Hollis, Fulford, Considine, &
200 Mattes, 2009; Higgs & Jones, 2013; Hogenkamp, Mars, Stafleu, & de Graaf, 2010, 2012;
201 Hogenkamp, Stafleu, Mars, & de Graaf, 2012; Smit, Kemsley, Tapp, & Henry, 2011; Zijlstra, Mars,
202 Stafleu, & de Graaf, 2010; Zijlstra, et al., 2008, Study 1 and 2; Zijlstra, de Wijk, Mars, Stafleu, & de
203 Graaf, 2009) and in the case of the study by Ferriday, et al. (2016) additional data was made publicly
204 available online (Bosworth, 2015).

205 All studies selected for qualitative synthesis were well-controlled experiments, in which
206 participants were randomly assigned to experimental conditions. Of the 42 studies, all but two were

207 laboratory based (Zijlstra, et al., 2010; Zijlstra, et al., 2008, Study 1) and all but two had a within
208 subjects design (Higgs & Jones, 2013; Hogenkamp, et al., 2010). In only 10 of the studies, a power
209 calculation was used to determine the number of participants needed to find a meaningful
210 significant difference (Ferriday, et al., 2016; Forde, et al., 2013; Hogenkamp, Mars, et al., 2012;
211 Lasschuijt, et al., 2017; Martens, Lemmens, Born, & Westerterp-Plantenga, 2011; Martin, et al.,
212 2007; McCrickerd, Lim, Leong, Chia, & Forde, 2017; Zhang, Leidy, & Vardhanabhuti, 2015; Zhu
213 & Hollis, 2014; Zhu, Hsu, & Hollis, 2013).

214 The total number of participants of all 40 studies included in the quantitative synthesis was 1711,
215 arising from studies with samples varying from 9 to 120 participants, and involved mainly young
216 adults (mean 25.1 years). Ideally studies should have an equal ratio of men to women, however for
217 a number of studies more women than men were included, with six studies using more than 70%
218 women (Bolhuis, et al., 2014; Hetherington & Regan, 2011; Higgs & Jones, 2013; Hogenkamp,
219 Mars, et al., 2012; Weijzen, Liem, Zandstra, & de Graaf, 2008; Zijlstra, et al., 2011). On the other
220 hand, five studies included only males (Bolhuis, Lakemond, de Wijk, Luning, & de Graaf, 2011;
221 Labouré, van Wymelbeke, Fantino, & Nicolaidis, 2002; Li, et al., 2011; Martens, et al., 2011; Zhu,
222 et al., 2013), whereas only four studies included just females (Andrade, Greene, & Melanson, 2008;
223 Komai, et al., 2016; Park, et al., 2016; Spiegel, Kaplan, Tomassini, & Stellar, 1993). Weight status
224 varied across studies, with 20 studies specifically selecting participants within a healthy BMI range,
225 five studies selecting people from specific weight groups to control for the influence of weight
226 status whereas the remaining 15 studies did not specifically select or control for BMI. From those
227 studies, there were two that also included participants with a BMI higher than 25 (Julis & Mattes,
228 2007; Martin, et al., 2007). In most studies (29 out of 40), participants with any dietary restriction
229 or dramatic weight change were specifically excluded as well as those who reported high levels of
230 dietary restraint (27 out of 40) as assessed by either the Dutch Eating Behavior Questionnaire
231 (DEBQ) (van Strien, Frijters, Bergers, & Defares, 1986) or the Three Factor Eating Questionnaire

232 (TFEQ) (Stunkard & Messick, 1985). None of the studies were double blinded, however in 22
233 studies the participants were distracted from the true aim through the use of a cover story.

234 In all studies, the researchers intended to vary only one characteristic of oral processing. However
235 manipulating one characteristic inevitably had an effect on other characteristics (i.e. a higher eating
236 rate might directly shorten the oral residence time). In 16 studies a test food was given with
237 manipulated texture, such as liquid versus semi-solid food, and in two studies a texture complexity
238 component was added. In six studies the number of chews per bite was manipulated, in three studies
239 the oral residence time was directly influenced, and in five studies participants were instructed to
240 eat at a specific chewing rate. Another three studies were included where the bite size was changed,
241 and the final six studies looked at the influence of chewing gum on satiety and food intake during
242 a later meal. For the purpose of the meta-analysis, the minimum and maximum oral processing
243 characteristics were compared to one another (see **Table 1**). The maximum values were set as the
244 commonly recommended values for reducing food intake and controlling appetite, such as small
245 bites, high number of chews and long oral residence time (Christen & Christen, 1997; Smit, et al.,
246 2011). In addition to the 26 studies that directly compared two oral processing parameters, the
247 remaining 14 studies examined other intermediate oral processing conditions that were not
248 considered in this systematic review. However, in the case of the study by Zijlstra, de Wijk, et al.
249 (2009) more separate conditions were considered in the meta-analysis; i.e., conditions comparing
250 different oral residence times after ingestion of free-choice boluses of liquid food (which the authors
251 called “bites”) as well as small and large boluses delivered with a peristaltic pump.

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

257 **Meta-analysis**

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

273 The meta-analysis was conducted on three outcome measures: subjective appetite ratings of hunger
274 and desire to eat and objective measures of food intake (see **Supplementary Tables 2 and 3**).
275 Despite the importance of standardizing hunger levels before the oral processing manipulation, only
276 seven studies provided a standard or preload meal (Bolhuis, et al., 2011; Lasschuijt, et al., 2017;
277 Mourao, Bressan, Campbell, & Mattes, 2007; Zhang, et al., 2015; Zijlstra, et al., 2010; Zijlstra, et
278 al., 2008, Study 1 and 2). The oral processing intervention consisted of a fixed amount of food or
279 was an ad libitum meal where food intake was measured. In some studies ad libitum intake was
280 permitted during the oral processing intervention, and in others there was a fixed amount of food
281 consumed. In one study ad libitum intake was measured twice, once during the oral processing

282 intervention and again at the test meal (Bolhuis, et al., 2014). Appetite ratings were measured at
283 baseline on arrival in the lab and/or directly after the standard meal. Measurements were repeated
284 directly after the oral processing intervention, and in some cases at 30 minute or hourly intervals
285 after for a specific period of time.

286 Appetite ratings were measured on 100 mm Visual Analog Scales (VAS) or categorical rating
287 scales. The 10-point or 5-point scores were converted to a 100 point scale, so appetite ratings could
288 be better compared against each other. When appetite was assessed at multiple time points after the
289 oral processing manipulation, the ratings directly after the end of manipulation were retrieved. To
290 control for differences in appetite levels before the start of the study due to varying fasting states,
291 for example, the change in mean appetite level was computed (raw mean difference, e.g. hunger
292 level after chewing intervention minus the baseline hunger level). Food intake was measured after
293 the chewing manipulation in either weight (g) or energy (kcal or kJ). Where needed, given values
294 were converted to kcal to standardize the measurement units. Mean, standard deviation and sample
295 size for each group were extracted for all papers where they were reported. To account for
296 differences in the measurement scales, the standardized mean difference (SMD) was used to
297 compute the effect size (Borenstein, Hedges, Higgins, & Rothstein, 2009). The studies employing
298 a between subjects design were treated as independent studies, whereas the studies employing a
299 within subjects design were considered as dependent studies. For the food intake studies a
300 correlation coefficient of 0.5 was assumed and for the appetite studies a correlation coefficient of
301 0.2. Both correlation coefficients were based on the few studies where raw data was available to
302 determine the actual correlation coefficients (Cassady, et al., 2009; Ferriday, et al., 2016;
303 Hetherington & Boyland, 2007; Hogenkamp, Stafleu, et al., 2012; Smit, et al., 2011).

304 Since the studies from our sample used different methodologies, the meta-analysis was performed
305 using a random effects (RE) model. The heterogeneity was assessed with the I^2 statistic as indicator
306 for the percentage of statistically meaningful variability between studies. An I^2 value of 0% means
307 there is no heterogeneity that needs to be explained, values of 25% are considered low, 50%

308 moderate and above 75% is considered high (Higgins, Thompson, Deeks, & Altman, 2003). If
309 heterogeneity between studies was considered high, we tried to explain this further by implementing
310 a mixed effects (ME) model with a number of moderators, such as fasting time, participants' age
311 and BMI status. To investigate risk of publication bias across the studies, funnel plots were
312 produced. A funnel plot is used to visually represent high oral processing effect estimates from
313 individual studies against the standard error of each study. Typically the precision of an estimate
314 increases with the size of the study, with studies with a small sample size distributed towards the
315 bottom of the plot and studies with a larger sample size scattered towards the narrower top of the
316 funnel plot as they are more precise. The different shades of the funnel plot correspond to the 90%
317 confidence interval CI (white), 95% CI (light grey) and 99% CI (dark grey). The free statistical
318 software R[®] (version 3.3.1) and the metaphor package (version 1.9-9) were used to conduct the
319 meta-analyses (forest plots and funnel plots). The software Comprehensive Meta-Analysis (version
320 2.2) was used to conduct the sensitivity and group effect analyses, as well as the Egger's tests to
321 assess publication bias (Egger, Davey Smith, Schneider, & Minder, 1997).

322 **Results**

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

325 **Effect of food oral processing on appetite**

326 Based on the 42 studies that measured appetite ratings, 10 found significant effects on the appetite
327 ratings, such as hunger, fullness and desire to eat. This disparity in the results may be associated
328 with the study methodology employed, such as having a fixed amount of food to chew. For
329 example, Cassady, et al. (2009) provided their participants with a fixed amount of almonds to chew
330 for different number of times (10, 25 or 40 chews). They found that a larger number of chews
331 significantly reduced appetite. A fixed amount of food was also given during the manipulation of
332 oral processing in five other studies that found a significant effect on appetite (Ferriday, et al., 2016;

333 Forde, et al., 2013; Hogenkamp, Stafleu, et al., 2012; Zhu, et al., 2013; Zijlstra, de Wijk, et al.,
334 2009). When ad libitum meals were provided, participants ate until they reached a certain level of
335 fullness, so the change in appetite ratings was similar regardless of the amount consumed or how
336 much energy was ingested. If an excess amount of food is offered in an ad libitum meal, the
337 motivation to eat may be stronger than the oral processing manipulation itself.

338 **Effect of oral processing on food intake**

339 Four studies did not measure ad libitum food intake during or after the oral processing intervention
340 (Cassady, et al., 2009; Forde, et al., 2013; Komai, et al., 2016; Martens, et al., 2011), and therefore
341 were not considered in this section of the review. Thus, the total number of studies that measured
342 food intake was 38. Food intake was measured either at the same time as the oral processing
343 intervention occurred, e.g. number of chews was manipulated during an ad libitum meal (Li, et al.,
344 2011), or after the oral processing manipulation, e.g. Zhu, et al. (2013).

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

352 **Effect of lubrication on appetite and food intake**

353 Six articles were identified that mentioned some links between lubrication and satiety (see
354 **Supplementary Table 4**). McCrickerd, Chambers, and Yeomans (2014) tested the satiety effects
355 of fruit drinks varying in thickness and creaminess. The viscosity and lubrication profiles of the test
356 drinks showed that the thickened drinks were more viscous and more lubricating, having a lower

357 traction coefficient than the thin drinks. No effect was found on satiety ratings, but they did observe
358 a difference in food intake where female participants self-selected a smaller portion size when the
359 drink's visual sensory characteristics indicated it would be more satiating (McCrickerd, et al.,
360 2014). A limitation of this study was that participants were allowed to self-select their own portion
361 size in a glass from a larger amount of the drink in a jug, after assessing the sensory characteristics.
362 The results might have been clearer if the sensory aspects were evaluated by a different panel, and
363 if the panelists were instructed to drink directly from a larger or fixed amount to ensure satiation.
364 A mindful assessment of the drink attending to the sensory features of the drinks before ad libitum
365 intake might have influenced the results. Moreover, as also suggested by the authors, the portion
366 size effect might have had a bigger influence on intake than the texture manipulation. It was
367 suggested that the average portion size for men was bigger than the serving glass could hold, but
368 was smaller for women. Therefore the portion size could explain the lack of effect found in male
369 participants, while there was an effect for female participants.

370 In a study by Morell, Fiszman, Varela, and Hernando (2014) the effect of four different
371 hydrocolloids in milkshakes with similar viscosity during pouring and handling conditions on
372 expected satiety was investigated. They found that the starch granules (mainly in modified starch)
373 swell up and disintegrate in presence of artificial saliva. However, the structural properties of guar
374 gum and λ -carrageenan milkshakes remained more or less intact. In addition, the modified starch
375 milkshake had a higher expected satiety. It was hypothesized that expected satiety was more linked
376 to the initially perceived thickness and creaminess of foods and that the loss of structure in presence
377 of saliva is linked to a melting sensation of the modified starch in the mouth (Morell, et al., 2014).
378 However, this melting sensation could be a function of better lubrication, which in this case seems
379 to be related to higher expected satiety, suggesting later stages of oral processing could be just as
380 important to satiety perceptions as the initial stages. In addition, Stribeck analysis of these
381 milkshakes with or without saliva was not performed to confirm whether the milkshakes had
382 significantly different friction coefficients in the mixed regime. In another study by Morell,

383 Hernando, Llorca, and Fiszman (2015) the influence of different proteins and presence of starch in
384 yoghurts was studied in relation to expected satiety. In line with their previous study, it was found
385 that addition of starch, as well as addition of protein, increased expected satiety with whey protein
386 having more potential to increase expected satiety than skimmed milk powder. The breakdown of
387 starch in presence of saliva and linked melting sensation was not found here, as the starch granules
388 were incorporated in the protein network, aggregating upon exposure to artificial saliva (Morell, et
389 al., 2015).

390 In a study by Gavião, Engelen, and van der Bilt (2004) several oral processing characteristics of
391 different food products were determined. Dry Melba toast resulted in a longer oral residence time
392 with more chewing cycles, whereas the addition of margarine reduced the time until swallowing as
393 well as the number of chews. This was largely attributed to the lubricating effects of butter
394 facilitating bolus formation (Gavião, et al., 2004), however no quantitative tribological
395 measurement of the bolus was performed to confirm such findings. Joyner, Pernell, and Daubert
396 (2014) tested the friction behavior of acid milk gels with and without the addition of saliva. The
397 addition of saliva was found to cause a significant change in the frictional behavior of the acid milk
398 gels, with a stronger effect seen in samples containing starch (Joyner, et al., 2014). However, in
399 both of these studies no direct link was made with any satiety parameters. Finally, Lett, Norton, and
400 Yeomans (2016) have shown the effects of physicochemical characteristics (e.g. droplet size) of
401 model (emulsions) affecting hunger and food intake. They highlight that the tribological and
402 rheological properties of these emulsions are the same; however, exact coefficients of friction at
403 orally relevant speeds are not mentioned (Lett, Norton, et al., 2016; Lett, Yeomans, Norton, &
404 Norton, 2016). These reports suggests that there is growing interest in lubrication measurements
405 but these have yet to be studied in depth for a potential contribution (if any) to satiety and food
406 intake.

407 **Meta-analysis**

408 The 38 articles included in the meta-analysis were divided into 70 individual subgroups. The
409 narrative part of this systematic review indicated that for the two appetite ratings (hunger and desire
410 to eat), the different methodology of a fixed or ad libitum meal might have significant effects on
411 the study outcomes. The studies were divided into groups where either a fixed amount was used for
412 the oral processing manipulation (Type 1), or where an ad libitum amount of food was presented
413 (Type 2). For the meta-analysis on hunger ratings, 14 Type 1 studies including 22 subgroups and
414 14 Type 2 studies with 22 subgroups reported data. The studies where chewing gum was used to
415 manipulate oral processing, and thus no food was ingested, were not included in the meta-analysis
416 for appetite.

417 **Figure 2** shows the meta-analysis results of the Type 1 studies. The results confirmed that a higher
418 level of oral processing had a significant effect on reducing hunger ratings (-0.20 effect size, 95%
419 confidence interval CI: -0.30, -0.11, I^2 statistic = 0%). The meta-analysis was also performed with
420 both the Type 1 and Type 2 studies included, and the results remained similar (-0.21 effect size,
421 95% CI: -0.27, -0.15, I^2 = 0%). The ME model using moderators indicated that the included
422 moderators were unable to better explain the total amount of heterogeneity, as the heterogeneity
423 level was already 0%. Subgroup analysis revealed that the oral processing variables eating rate and
424 texture had a significant effect on hunger ratings, whereas bite size, oral residence time, number of
425 chews and texture complexity on their own did not affect hunger. It is however important to note
426 that few studies were included for the latter variables, where no significant effect was found. For
427 the desire to eat ratings, 9 studies including 15 subgroups reported data. The meta-analysis showed
428 similar results to that of the hunger ratings namely that higher oral processing reduced self-reported
429 desire to eat (-0.21 effect size, 95% CI: -0.31, -0.10, I^2 = 0%, see **Supplementary Figure 1**).

430 Meta-analysis of the food intake data included 35 studies with 65 subgroups. Study 2 by de Wijk,
431 et al. (2008) did not provide the standard deviations for food intake and therefore was not included
432 in the meta-analysis. A significant effect of oral processing reducing food intake was found (-0.28

433 effect size, 95% CI: -0.36, -0.19, $I^2 = 61.52\%$), as can be observed in **Figure 3**. This is in line with
434 what we expected, given the large amount of individual studies that found a significant effect. The
435 I^2 value did indicate a moderate level of heterogeneity, however the ME model using moderators
436 did not result in a consistent improvement. Subgroup analysis revealed that there was no significant
437 effect of oral residence time alone on food intake, however there were only two studies that looked
438 specifically at oral residence time. The other oral processing factors all included more than two
439 studies, and all showed a significant effect on reducing food intake. Furthermore, as there are
440 different processes that might affect food intake over time, such as cephalic-phase responses in
441 anticipation of food after eating chewing gum or cognitive processes due to the increased expected
442 satiating power of harder, thicker and chewier food, the meta-analysis outcome was tested when
443 Type 1 studies were excluded. However, when only looking at the studies that measured ad libitum
444 food intake at the same time as the oral processing intervention, the outcome was not affected (-0.45
445 effect size, 95% CI: -0.55, -0.35, $I^2 = 69.06\%$).

446 Publication bias was assessed using funnel plots and the Egger's regression test. The funnel plot
447 for the hunger ratings (**Figure 4**) shows a relatively good distribution over the vertical axis,
448 indicating that studies with different sample sizes were included. However, the majority of the
449 studies clustered towards to the left of the mean, indicating there might be evidence of publication
450 bias. Nevertheless, this visual impression was not supported by the Egger's test ($P = 0.17$, CI: -
451 1.01, 0.18). The asymmetry in the funnel plot for food intake in **Figure 5** also shows a potential
452 bias in favor of studies that found oral processing had an effect on lowering food intake. This was
453 confirmed by the Eggers's test ($P = 0.000$, CI: -3.59, -1.25).

454 **Discussion**

455 The main aim of this comprehensive systematic review and meta-analysis was to understand the
456 impact of oral processing, including chewing and lubrication, on appetite and food intake. It was
457 hypothesized that enhanced oral processing would affect appetite sensations, and reduce food

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

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

478 The results of these meta-analyses suggest that varying different components of oral processing
479 taken together, can have a significant influence on reducing hunger ratings and food intake. Overall,
480 from the literature included in this systematic review, it is clear that all studies involved a relatively
481 low number of participants (varying from 9 to 120) and a short-term intervention (only once in most
482 studies). Studies with a larger sample size involving longer well-described replicable interventions

483 (from weeks to months) are needed to understand the impact of oral processing on long-term satiety
484 enhancement and its potential in weight management. In addition, product differences need to be
485 large enough to be detectable by consumers to find a potential influence due to oral processing.

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

500 A systematic review and meta-analysis by Robinson, et al. (2014) studied the effects of the specific
501 oral processing characteristic of eating rate on hunger and energy intake. They concluded that a
502 slower eating rate led to a lower energy intake as compared to a faster eating rate, and that different
503 ways in which eating rate could be manipulated (directly or indirectly) did not alter the outcome.
504 No effect of eating rate on hunger was found directly after the meal or up to 3.5h after the meal,
505 both in the analysis with ad libitum studies as well as the fixed studies. The difference with our
506 results on the hunger ratings could be explained by including more oral processing variables, and
507 also many more studies were included (five compared to 22 subgroups in the current review with
508 fixed amounts of foods). Another systematic review by Miquel-Kergoat, et al. (2015) compared the

509 outcome measure of hunger ratings and energy intake under different oral processing conditions,
510 with the addition of gut hormones and metabolites. Besides hunger ratings, meta-analyses in the
511 current review focused on food intake and desire to eat data, thereby broadening the scope of the
512 review. Also, the oral processing definition was expanded to include aspects of lubrication and
513 saliva incorporation. Finally, oral processing parameters were grouped together according to the
514 recommended oral processing strategies commonly suggested for better weight management such
515 as slow eating rates, high number of chews and longer oral resident time (Christen & Christen,
516 1997; Ford, et al., 2010; Smit, et al., 2011). Moreover, additional data not included in the original
517 publication was requested from authors. Instead of comparing 13 subgroups as was reported by
518 Miquel-Kergoat, et al. (2015), the current review included hunger ratings from 22 subgroups.
519 Therefore, the present review allows a more comprehensive and advanced analysis by broadening
520 the scope of the used measures, expanding the search to include lubrication, and performing detailed
521 analysis using raw data from authors.

522 **Conclusions**

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

530 Although evidence was found for the effects of oral processing on appetite ratings and food intake,
531 this systematic review identified a clear gap in knowledge on the influence of saliva incorporation
532 and oral lubrication on appetite ratings and food intake. The influence of the lubrication parameters
533 of food (pre and post mixing with saliva) on appetite and food intake remains largely unquantified.

534 Furthermore, the studies involving lubrication did not perform tribological measurements of the
535 food and the bolus to quantify differences in lubrication profiles. Future research should be
536 conducted following the framework outlined by Blundell, et al. (2010) and standardize prior hunger
537 before oral processing manipulations, which should be apparent and not subtle. With carefully
538 planned and standardized procedures, the knowledge base on the importance of all aspects of oral
539 processing, including both chewing and lubrication, for satiation and satiety development will be
540 expanded and potential application to weight management can be explored. Such knowledge,
541 together with longer interventions, are needed to underpin the creation of the next generation of
542 foods for weight management and allow the development of coordinated public health strategies to
543 tackle obesity.

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549 **Author contributions statement**

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

556 **Conflict of interest statement**

557 None.

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561 **References**

- 562 Andrade, A. M., Greene, G. W., & Melanson, K. J. (2008). Eating slowly led to decreases in energy
563 intake within meals in healthy women. *Journal of the American Dietetic Association*, 108,
564 1186-1191.
- 565 Blundell, J. E., de Graaf, C., Finlayson, G., Halford, J. C. G., Hetherington, M. M., King, N. A., &
566 Stubbs, J. (2009). Measuring food intake, hunger, satiety and satiation in the laboratory. In
567 D. B. Allison & M. L. Baskin (Eds.), *Handbook of Assessment Methods for Eating*
568 *Behaviours and Weight-Related Problems : Measures, Theory and Research [2nd. ed.]*
569 (pp. 283-325). Newbury Park, California: Sage.
- 570 Blundell, J. E., de Graaf, C., Hulshof, T., Jebb, S., Livingstone, B., Luch, A., Mela, D., Salah, S.,
571 Schuring, E., van der Knaap, H., & Westerterp, M. (2010). Appetite control: methodological
572 aspects of the evaluation of foods. *Obesity Reviews*, 11, 251-270.
- 573 Bolhuis, D. P., Forde, C. G., Cheng, Y., Xu, H., Martin, N., & de Graaf, C. (2014). Slow food:
574 sustained impact of harder foods on the reduction in energy intake over the course of the
575 day. *PLoS One*, 9, e93370.
- 576 Bolhuis, D. P., Lakemond, C. M. M., de Wijk, R. A., Luning, P. A., & de Graaf, C. (2011). Both
577 longer oral sensory exposure to and higher intensity of saltiness decrease ad libitum food
578 intake in healthy normal-weight men. *Journal of Nutrition*, 141, 2242-2248.
- 579 Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). Effect sizes based on
580 means. In *Introduction to Meta-Analysis* (pp. 21-32): John Wiley & Sons, Ltd.
- 581 Bosworth, M. L. (2015). Variation in the oral processing of everyday meals is associated with
582 fullness and meal size; a potential nudge to reduce energy intake. In: data.bris Research
583 Data Repository.
- 584 Cassady, B. A., Hollis, J. H., Fulford, A. D., Considine, R. V., & Mattes, R. D. (2009). Mastication
585 of almonds: effects of lipid bioaccessibility, appetite, and hormone response. *Am J Clin*
586 *Nutr*, 89, 794-800.
- 587 Chen, J. (2009). Food oral processing - a review. *Food Hydrocolloids*, 23, 1-25.
- 588 Chen, J., & Stokes, J. R. (2012). Rheology and tribology: two distinctive regimes of food texture
589 sensation. *Trends in Food Science & Technology*, 25, 4-12.
- 590 Christen, A. G., & Christen, J. A. (1997). Horace Fletcher (1849-1919): "The Great Masticator." .
591 *Journal of the History of Dentistry*, 45, 95-100.
- 592 Egger, M., Davey Smith, G., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected
593 by a simple, graphical test. *Bmj*, 315, 629-634.
- 594 Ferriday, D., Bosworth, M. L., Godinot, N., Martin, N., Forde, C. G., van den Heuvel, E., Appleton,
595 S. L., Moss, F. J. M., Rogers, P. J., & Brunstrom, J. M. (2016). Variation in the oral
596 processing of everyday meals is associated with fullness and meal size; A potential nudge
597 to reduce energy intake? *Nutrients*, 8.

- 598 Ford, A. L., Bergh, C., Södersten, P., Sabin, M. A., Hollinghurst, S., Hunt, L. P., & Shield, J. P. H.
599 (2010). Treatment of childhood obesity by retraining eating behaviour: randomised
600 controlled trial. *Bmj*, 340.
- 601 Forde, C. G., Kuijk, N., Thaler, T., de Graaf, C., & Martin, N. (2013). Oral processing
602 characteristics of solid savoury meal components, and relationship with food composition,
603 sensory attributes and expected satiation. *Appetite*, 60, 208-219.
- 604 Gavião, M. B. D., Engelen, L., & van der Bilt, A. (2004). Chewing behavior and salivary secretion.
605 *European Journal of Oral Sciences*, 112, 19-24.
- 606 Giduck, S. A., Threatte, R. M., & Kare, M. R. (1987). Cephalic reflexes: their role in digestion and
607 possible roles in absorption and metabolism. *J Nutr*, 117, 1191-1196.
- 608 Hetherington, M. M., & Boyland, E. (2007). Short-term effects of chewing gum on snack intake
609 and appetite. *Appetite*, 48, 397-401.
- 610 Hetherington, M. M., Cunningham, K., Dye, L., Gibson, E. L., Gregersen, N. T., Halford, J. C.,
611 Lawton, C. L., Lluch, A., Mela, D. J., & van Trijp, H. C. (2013). Potential benefits of satiety
612 to the consumer: scientific considerations. *Nutr Res Rev*, 26, 22-38.
- 613 Hetherington, M. M., & Regan, M. F. (2011). Effects of chewing gum on short-term appetite
614 regulation in moderately restrained eaters. *Appetite*, 57, 475-482.
- 615 Higgins, J. P. T., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency
616 in meta-analyses. *Bmj*, 327, 557-560.
- 617 Higgs, S., & Jones, A. (2013). Prolonged chewing at lunch decreases later snack intake. *Appetite*,
618 62, 91-95.
- 619 Hill, J. O. (2006). Understanding and Addressing the Epidemic of Obesity: An Energy Balance
620 Perspective. *Endocrine Reviews*, 27, 750-761.
- 621 Hogenkamp, P. S., Mars, M., Stafleu, A., & de Graaf, C. (2010). Intake during repeated exposure
622 to low- and high-energy-dense yogurts by different means of consumption. *Am J Clin Nutr*,
623 91, 841-847.
- 624 Hogenkamp, P. S., Mars, M., Stafleu, A., & de Graaf, C. (2012). Repeated consumption of a large
625 volume of liquid and semi-solid foods increases ad libitum intake, but does not change
626 expected satiety. *Appetite*, 59, 419-424.
- 627 Hogenkamp, P. S., & Schiöth, H. B. (2013). Effect of oral processing behaviour on food intake and
628 satiety. *Trends in Food Science and Technology*, 34, 67-75.
- 629 Hogenkamp, P. S., Stafleu, A., Mars, M., & de Graaf, C. (2012). Learning about the energy density
630 of liquid and semi-solid foods. *International Journal of Obesity*, 36, 1229-1235.
- 631 Joyner, H. S., Pernell, C. W., & Daubert, C. R. (2014). Impact of formulation and saliva on acid
632 milk gel friction behavior. *Journal of Food Science*, 79, E867-E880.
- 633 Julis, R. A., & Mattes, R. D. (2007). Influence of sweetened chewing gum on appetite, meal
634 patterning and energy intake. *Appetite*, 48, 167-175.
- 635 Komai, N., Motokubota, N., Suzuki, M., Hayashi, I., Moritani, T., & Nagai, N. (2016). Thorough
636 mastication prior to swallowing increases postprandial satiety and the thermic effect of a
637 meal in young women. *Journal of Nutritional Science and Vitaminology*, 62, 288-294.
- 638 Labouré, H., van Wymelbeke, V., Fantino, M., & Nicolaidis, S. (2002). Behavioral, plasma, and
639 calorimetric changes related to food texture modification in men. *American Journal of
640 Physiology - Regulatory Integrative and Comparative Physiology*, 282, R1501-R1511.

- 641 Laguna, L., Farrell, G., Bryant, M., Morina, A., & Sarkar, A. (2017). Relating rheology and
642 tribology of commercial dairy colloids to sensory perception. *Food & Function*, 8, 563-573.
- 643 Laguna, L., & Sarkar, A. (2016). Influence of mixed gel structuring with different degrees of matrix
644 inhomogeneity on oral residence time. *Food Hydrocolloids*, 61, 286-299.
- 645 Laguna, L., & Sarkar, A. (2017). Oral tribology: update on the relevance to study astringency in
646 wines. *Tribology - Materials, Surfaces & Interfaces*, 11, 116-123.
- 647 Larsen, D. S., Tang, J., Ferguson, L. R., & James, B. J. (2016). Increased textural complexity in
648 food enhances satiation. *Appetite*, 105, 189-194.
- 649 Lasschuijt, M. P., Mars, M., Stieger, M., Miquel-Kergoat, S., de Graaf, C., & Smeets, P. A. M.
650 (2017). Comparison of oro-sensory exposure duration and intensity manipulations on
651 satiation. In *Physiology and behavior*. (no pagination), 2017 (Vol. Date of Publication:
652 November 08).
- 653 Lavin, J. H., French, S. J., Ruxton, C. H. S., & Read, N. W. (2002). An investigation of the role of
654 oro-sensory stimulation in sugar satiety. *International Journal of Obesity*, 26, 384-388.
- 655 Lett, A. M., Norton, J. E., & Yeomans, M. R. (2016). Emulsion oil droplet size significantly affects
656 satiety: A pre-ingestive approach. *Appetite*, 96, 18-24.
- 657 Lett, A. M., Yeomans, M. R., Norton, I. T., & Norton, J. E. (2016). Enhancing expected food intake
658 behaviour, hedonics and sensory characteristics of oil-in-water emulsion systems through
659 microstructural properties, oil droplet size and flavour. *Food Quality and Preference*, 47,
660 148-155.
- 661 Li, J., Zhang, N., Hu, L., Li, Z., Li, R., Li, C., & Wang, S. (2011). Improvement in chewing activity
662 reduces energy intake in one meal and modulates plasma gut hormone concentrations in
663 obese and lean young Chinese men. *Am J Clin Nutr*, 94, 709-716.
- 664 Martens, M. J., Lemmens, S. G., Born, J. M., & Westerterp-Plantenga, M. S. (2011). A solid high-
665 protein meal evokes stronger hunger suppression than a liquefied high-protein meal. *Obesity*
666 (Silver Spring, Md.), 19, 522-527.
- 667 Martin, C. K., Anton, S. D., Walden, H., Arnett, C., Greenway, F. L., & Williamson, D. A. (2007).
668 Slower eating rate reduces the food intake of men, but not women: Implications for
669 behavioral weight control. *Behaviour Research and Therapy*, 45, 2349-2359.
- 670 Mattes, R. D., & Considine, R. V. (2013). Oral processing effort, appetite and acute energy intake
671 in lean and obese adults. *Physiology & Behavior*, 120, 173-181.
- 672 McCrickerd, K., Chambers, L., & Yeomans, M. R. (2014). Does modifying the thick texture and
673 creamy flavour of a drink change portion size selection and intake? *Appetite*, 73, 114-120.
- 674 McCrickerd, K., Lim, C. M., Leong, C., Chia, E. M., & Forde, C. G. (2017). Texture-based
675 differences in eating rate reduce the impact of increased energy density and large portions
676 on meal size in adults. *J Nutr*.
- 677 Miquel-Kergoat, S., Azais-Braesco, V., Burton-Freeman, B., & Hetherington, M. M. (2015).
678 Effects of chewing on appetite, food intake and gut hormones: a systematic review and
679 meta-analysis. *Physiology and Behavior*, 151, 88-96.
- 680 Moore, C. L. (2012). The caring experience of staff carers working with adults with learning
681 disability and dementia. University of Hull.
- 682 Morell, P., Fiszman, S. M., Varela, P., & Hernando, I. (2014). Hydrocolloids for enhancing satiety:
683 relating oral digestion to rheology, structure and sensory perception. *Food Hydrocolloids*,
684 41, 343-353.

- 685 Morell, P., Hernando, I., Llorca, E., & Fiszman, S. M. (2015). Yogurts with an increased protein
686 content and physically modified starch: rheological, structural, oral digestion and sensory
687 properties related to enhanced satiating capacity. *Food Research International*, 70, 64-73.
- 688 Mourao, D. M., Bressan, J., Campbell, W. W., & Mattes, R. D. (2007). Effects of food form on
689 appetite and energy intake in lean and obese young adults. *Int J Obes*, 31, 1688-1695.
- 690 Nolan, L. J., & Hetherington, M. M. (2009). The effects of sham feeding-induced sensory specific
691 satiation and food variety on subsequent food intake in humans. *Appetite*, 52, 720-725.
- 692 Park, E., Edirisinghe, I., Inui, T., Miquel-Kergoat, S., Kelley, M., & Burton-Freeman, B. (2016).
693 Short-term effects of chewing gum on satiety and afternoon snack intake in healthy weight
694 and obese women. *Physiology & Behavior*, 159, 64-71.
- 695 Robinson, E., Almiron-Roig, E., Rutters, F., de Graaf, C., Forde, C. G., Tudur Smith, C., Nolan, S.
696 J., & Jebb, S. A. (2014). A systematic review and meta-analysis examining the effect of
697 eating rate on energy intake and hunger. *Am J Clin Nutr*, 100, 123-151.
- 698 Sarkar, A., & Singh, H. (2012). Oral behaviour of food emulsions. In *Food Oral Processing* (pp.
699 111-137): Wiley-Blackwell.
- 700 Sarkar, A., Ye, A., & Singh, H. (2017). Oral processing of emulsion systems from a colloidal
701 perspective. *Food & Function*, 8, 511-521.
- 702 Smit, H. J., Kemsley, E. K., Tapp, H. S., & Henry, C. J. K. (2011). Does prolonged chewing reduce
703 food intake? Fletcherism revisited. *Appetite*, 57, 295-298.
- 704 Spiegel, T. A., Kaplan, J. M., Tomassini, A., & Stellar, E. (1993). Bite size, ingestion rate, and meal
705 size in lean and obese women. *Appetite*, 21, 131-145.
- 706 Stokes, J. R., Boehm, M. W., & Baier, S. K. (2013). Oral processing, texture and mouthfeel: From
707 rheology to tribology and beyond. *Current Opinion in Colloid & Interface Science*, 18, 349-
708 359.
- 709 van Strien, T., Frijters, J. E. R., Bergers, G. P. A., & Defares, P. B. (1986). The Dutch Eating
710 Behavior Questionnaire (DEBQ) for assessment of restrained, emotional, and external
711 eating behavior. *International Journal of Eating Disorders*, 5, 295-315.
- 712 Stubbs, R. J., Hughes, D. A., Johnstone, A. M., Rowley, E., Reid, C., Elia, M., Stratton, R., Delargy,
713 H., King, N., & Blundell, J. E. (2000). The use of visual analogue scales to assess motivation
714 to eat in human subjects: a review of their reliability and validity with an evaluation of new
715 hand-held computerized systems for temporal tracking of appetite ratings. *The British
716 journal of nutrition*, 84, 405-415.
- 717 Stunkard, A. J., & Messick, S. (1985). The three-factor eating questionnaire to measure dietary
718 restraint, disinhibition and hunger. *J Psychosom Res*, 29, 71-83.
- 719 Swoboda, C., & Temple, J. L. (2013). Acute and chronic effects of gum chewing on food
720 reinforcement and energy intake. *Eating Behaviors*, 14, 149-156.
- 721 Tang, J., Larsen, D. S., Ferguson, L. R., & James, B. J. (2016). The effect of textural complexity of
722 solid foods on satiation. *Physiol Behav*, 163, 17-24.
- 723 Viskaal-van Dongen, M., Kok, F. J., & de Graaf, C. (2011). Eating rate of commonly consumed
724 foods promotes food and energy intake. *Appetite*, 56, 25-31.
- 725 Weijzen, P. L. G., Liem, D. G., Zandstra, E. H., & de Graaf, C. (2008). Sensory specific satiety and
726 intake: the difference between nibble- and bar-size snacks. *Appetite*, 50, 435-442.
- 727 de Wijk, R. A., Zijlstra, N., Mars, M., de Graaf, C., & Prinz, J. F. (2008). The effects of food
728 viscosity on bite size, bite effort and food intake. *Physiology & Behavior*, 95, 527-532.

- 729 World Health Organization. (2000). Obesity: preventing and managing the global epidemic. In
730 Technical Report Series 894 (pp. 252).
- 731 World Health Organization. (2016). Obesity and overweight. In Fact sheet N°311: World Health
732 Organization.
- 733 Zandian, M., Ioakimidis, I., Bergh, C., Brodin, U., & Södersten, P. (2009). Decelerated and linear
734 eaters: effect of eating rate on food intake and satiety. *Physiology & Behavior*, 96, 270-275.
- 735 Zhang, S., Leidy, H. J., & Vardhanabhuti, B. (2015). Protein beverage vs. protein gel on appetite
736 control and subsequent food intake in healthy adults. *Nutrients*, 7, 8700-8711.
- 737 Zhu, Y., & Hollis, J. H. (2014). Increasing the number of chews before swallowing reduces meal
738 size in normal-weight, overweight, and obese adults. *Journal of the Academy of Nutrition
739 and Dietetics*, 114, 926-931.
- 740 Zhu, Y., Hsu, W. H., & Hollis, J. H. (2013). Increasing the number of masticatory cycles is
741 associated with reduced appetite and altered postprandial plasma concentrations of gut
742 hormones, insulin and glucose. *The British journal of nutrition*, 110, 384-390.
- 743 Zijlstra, N., Bukman, A. J., Mars, M., Stafleu, A., Ruijschop, R. M., & de Graaf, C. (2011). Eating
744 behaviour and retro-nasal aroma release in normal-weight and overweight adults: a pilot
745 study. *The British journal of nutrition*, 106, 297-306.
- 746 Zijlstra, N., Mars, M., Stafleu, A., & de Graaf, C. (2010). The effect of texture differences on
747 satiation in 3 pairs of solid foods. *Appetite*, 55, 490-497.
- 748 Zijlstra, N., Mars, M., de Wijk, R. A., Westerterp-Plantenga, M. S., & de Graaf, C. (2008). The
749 effect of viscosity on ad libitum food intake. *Int J Obes*, 32, 676-683.
- 750 Zijlstra, N., Mars, M., de Wijk, R. A., Westerterp-Plantenga, M. S., Holst, J. J., & de Graaf, C.
751 (2009). Effect of viscosity on appetite and gastro-intestinal hormones. *Physiol Behav*, 97,
752 68-75.
- 753 Zijlstra, N., de Wijk, R. A., Mars, M., Stafleu, A., & de Graaf, C. (2009). Effect of bite size and
754 oral processing time of a semisolid food on satiation. *Am J Clin Nutr*, 90, 269-275.

Figures

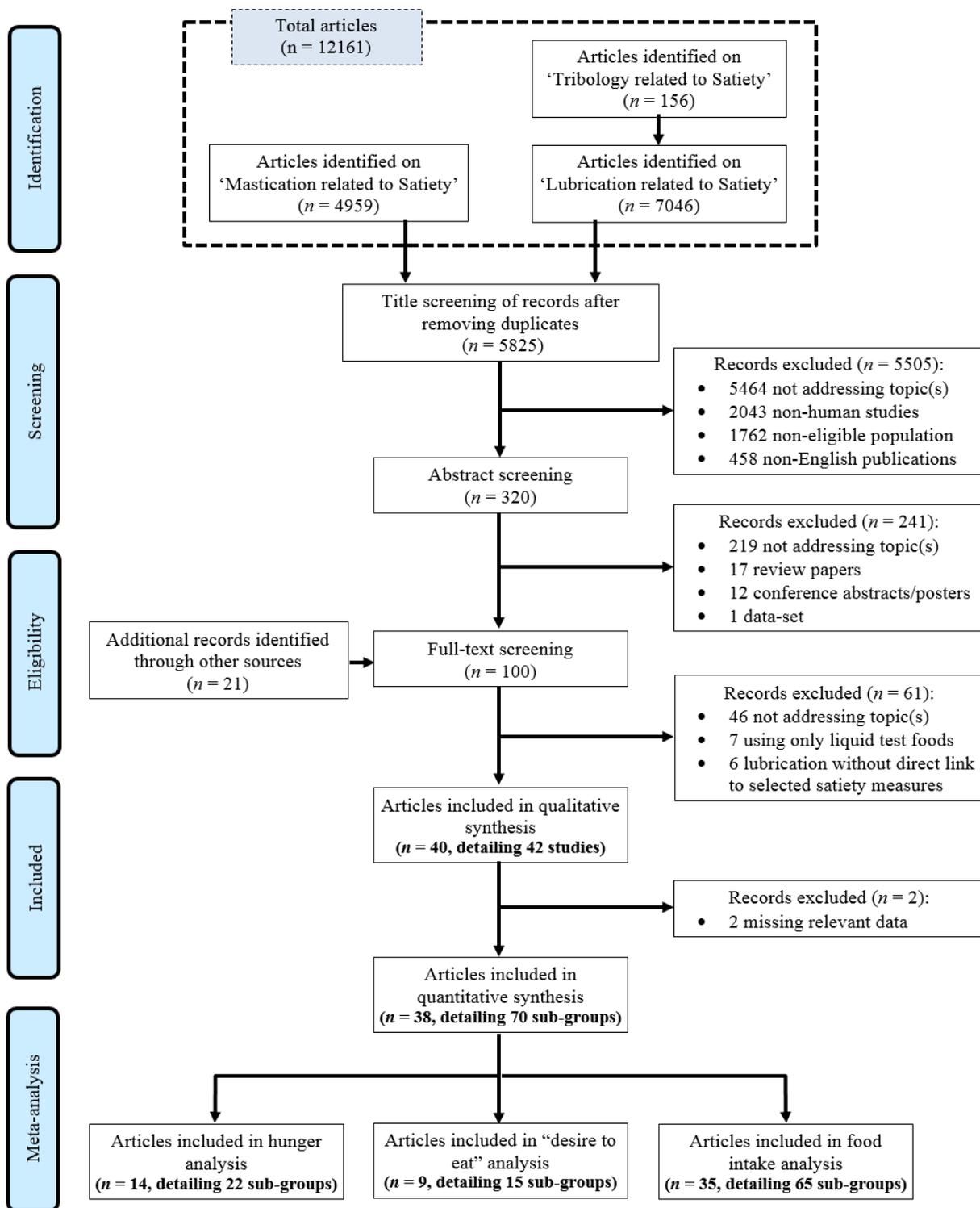


Figure 1: PRISMA flow-chart of the study selection procedure

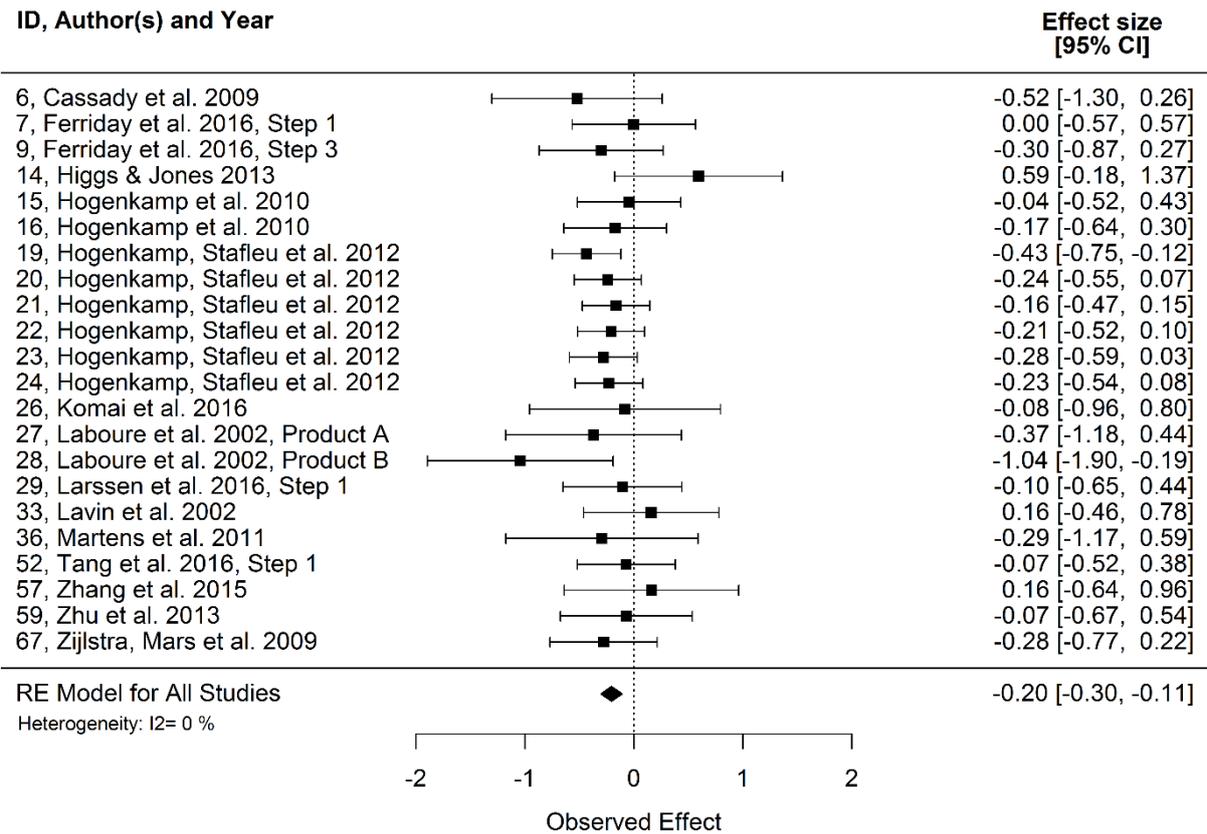


Figure 2: Forest plot of oral processing effects on the SMD of hunger ratings with corresponding 95% CI. The pooled estimates were obtained using RE modeling. The I^2 value is a measure of the approximate proportion of total variability in point estimates that can be attributed to heterogeneity.

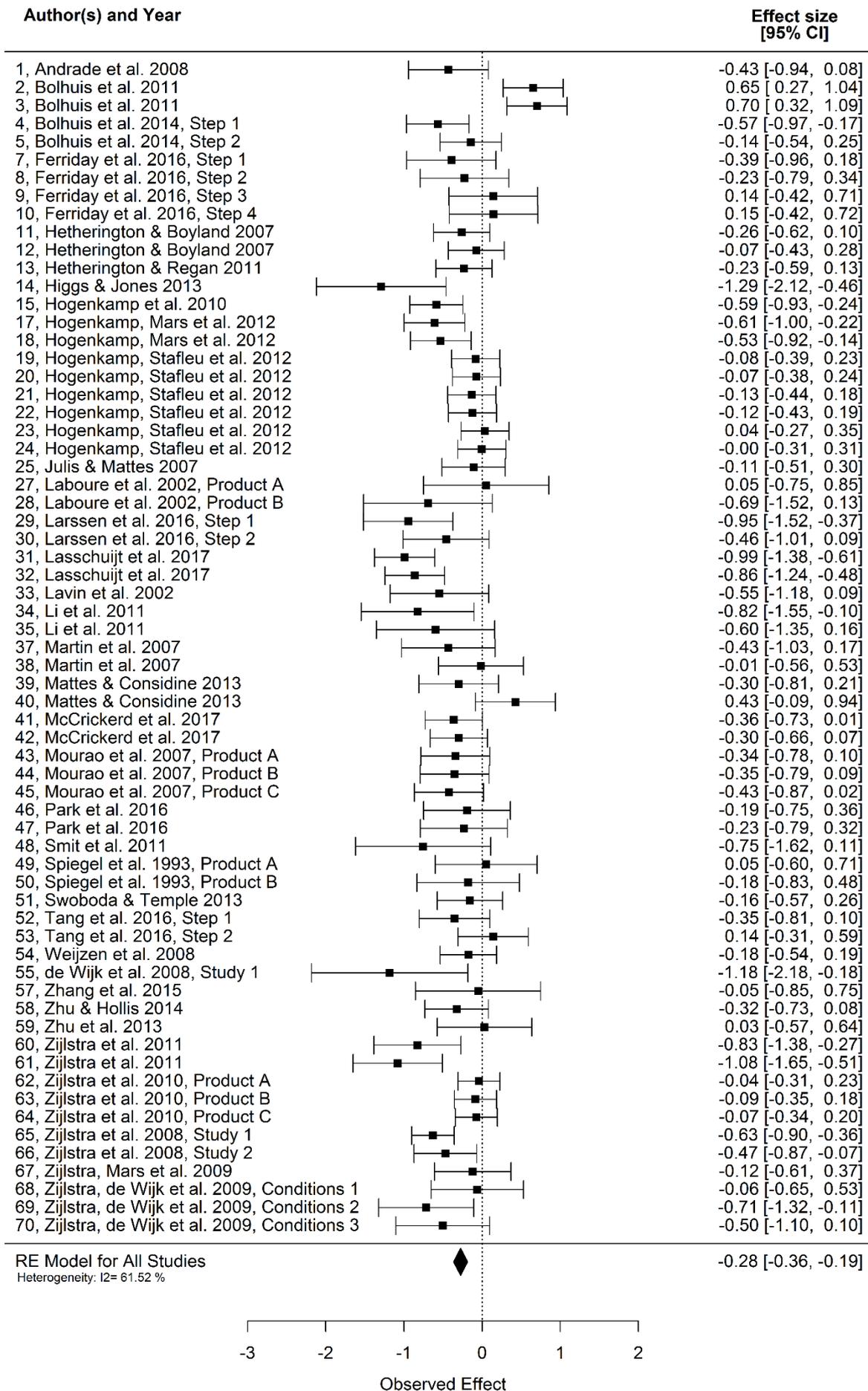


Figure 3: Forest plot of oral processing effects on the SMD of food intake with corresponding 95% CI. The pooled estimates were obtained using RE modeling.

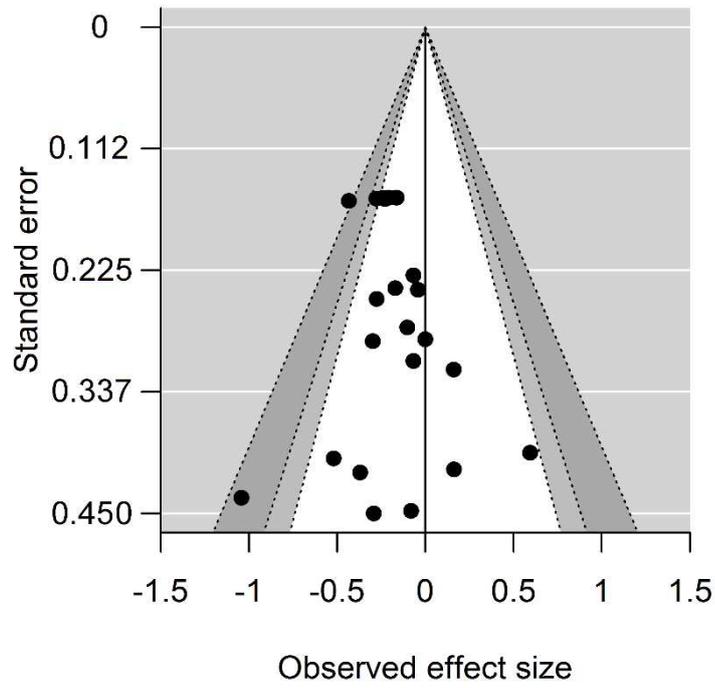


Figure 4: Funnel plot of oral processing effects on hunger ratings with the different shades corresponding to the 90% CI (white), 95% CI (light grey) and 99% CI (dark grey).

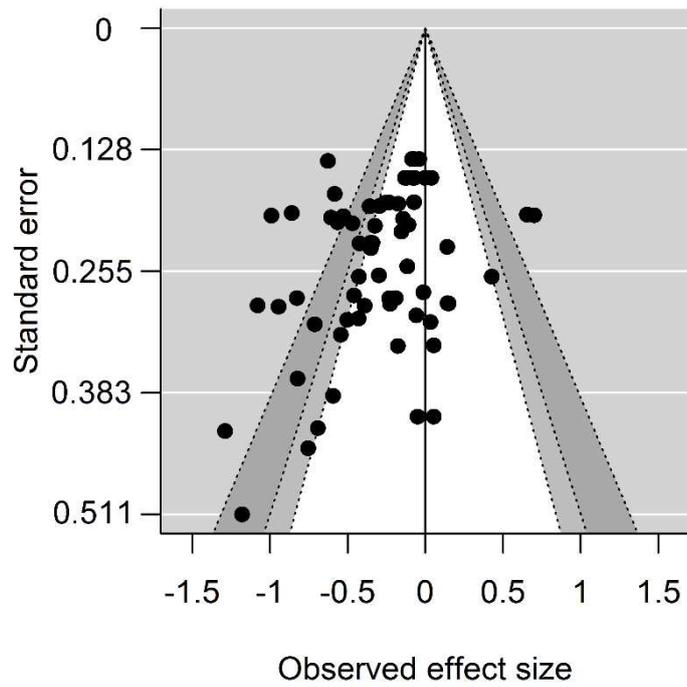


Figure 5: Funnel plot of oral processing effects on food intake with the different shades corresponding to the 90% CI (white), 95% CI (light grey) and 99% CI (dark grey).

Tables

Table 1: Oral processing parameters as compared across studies

Parameter¹	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

¹ 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).

Table 2: Characteristics of studies included in the systematic review¹

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, et al. (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, et al. (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, et al. (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)², 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, et al. (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

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
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 snack), with gum chewed at 4 time points after lunch and ad libitum intake measured 3h later	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
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, et al. (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, et al. (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, et al. (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

Reference	Participants			Study information			Outcomes				
	n	Gender (M/F)	BMI groups	Study design	Test food	Test procedure	Appetite method	Effect appetite	in	Food intake method	Effect food intake
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	Questionnaire	No difference in snack intake between chewing gum conditions
Komai, et al. (2016)³	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		NA
Labouré, et al. (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	Dinner energy and macro-nutrient content	No difference in energy intake at dinner
Larsen, et al. (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 two-course ad libitum meal	VAS	No difference	in	Weighing	Yes, ↓ intake after high complex food compared to low complex food
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	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	Weighing	Yes, energy intake ↓ after pastilles compared to water and the sweet drink
Li, et al. (2011)⁴	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	Weighing	Yes, after 40 chews energy intake ↓ than after 15 chews
Martens, et al. (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		NA

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
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, et al. (2017)⁵	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, et al. (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 libitum intake measured 3h later	VAS	Yes, chewing gum ↓ hunger over time compared to not chewing gum	Weighing	No difference in snack intake between chewing gum conditions
Smit, et al. (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

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
Spiegel, et al. (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)6	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, et al. (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, et al. (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

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
Zandian, et al. (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, et al. (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 control sample, followed by ad libitum lunch	VAS	No difference in appetite ratings	Weighing	No difference in food intake between protein snacks
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, et al. (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, et al. (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

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
Zijlstra, et al. (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, et al. (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

¹ CPM: Chews Per Mouthful, NW: Normal Weight, OB: Obese: OW: Over Weight, UW: Under Weight, VAS: Visual Analytical Scale

² Two studies were reported, only Study 2 was included in this review

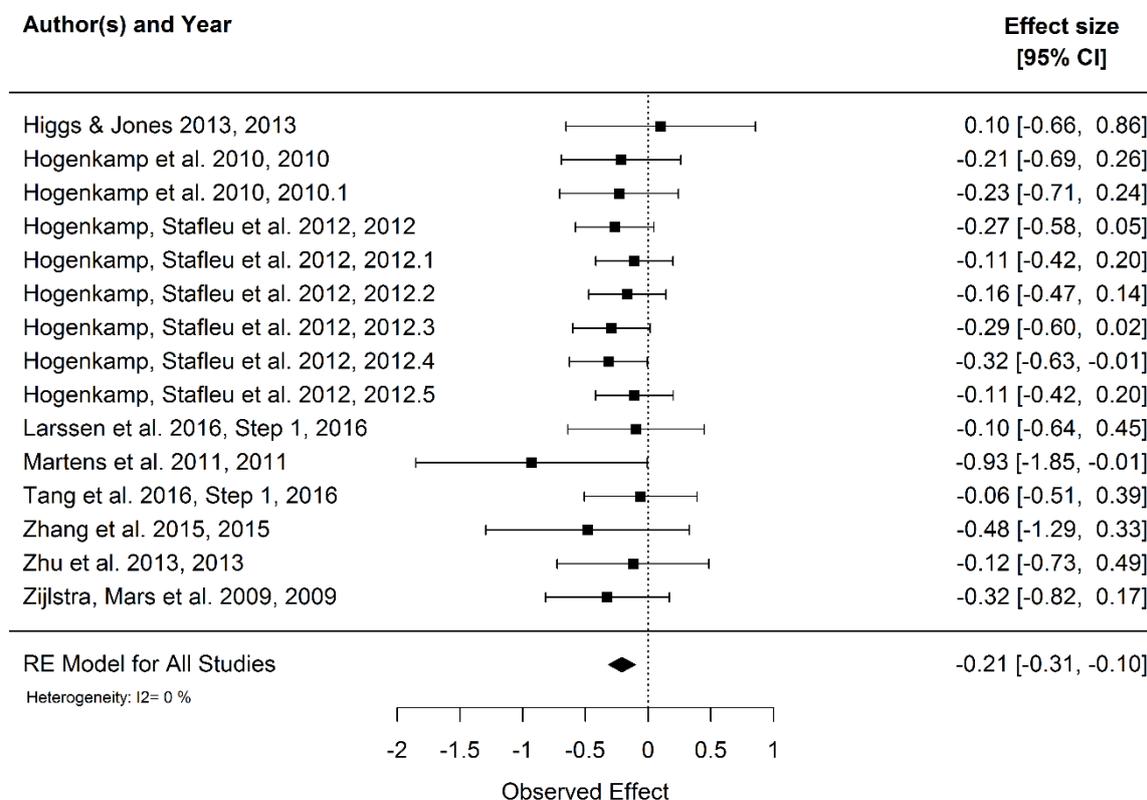
³ Two studies were reported, only Study 2 was included in this review

⁴ Two studies were reported, only Study 2 was included in this review

⁵ Two studies were reported, only Study 1 was included in this review

⁶ Two studies were reported, only Study 1 was included in this review

Supplementary data



Supplementary Figure 1: Forest plot of oral processing effects on the standardized mean difference (SMD) of desire to eat ratings with corresponding 95% confidence interval (CI). The pooled estimates were obtained using a random effects (RE) modeling.

Supplementary Table 1: Participant data of studies included in the meta-analyses

Study ID and reference	n 1	n 2	Male	Female	Mean Age \pm SD	Mean BMI \pm SD
1 Andrade, et al. (2008)	30		0	30	22.9 \pm 7.1	22.1 \pm 2.9
2 Bolhuis, et al. (2011), Part A + B	55		55	0	22.0 \pm 3.0	22.0 \pm 2.0
4 Bolhuis, et al. (2014), Step 1 + 2	50		11	39	24.0 \pm 2.0	21.0 \pm 2.0
6 Cassady, et al. (2009)	13		8	5	24.0 \pm 6.5	23.1 \pm 1.4
7 Ferriday, et al. (2016), Step 1 + 2 + 3 + 4	24		12	12	22.8 \pm 3.8	21.8 \pm 2.6
11 Hetherington and Boyland (2007), Part A + B	60		20	40	21.7 \pm 4.0	22.7 \pm 3.4
13 Hetherington and Regan (2011)	60		7	53	32.3 \pm 10.7	26.2 \pm 4.0
14 Higgs and Jones (2013)	14	13 ¹	7	34	20.6 \pm 8.8	21.0 \pm 8.2
15 Hogenkamp, et al. (2010), Part A + B	34	35 ²	36	33	22.0 \pm 3.0	21.6 \pm 1.7
17 Hogenkamp, Mars, et al. (2012), Part A + B	53		12	41	21.0 \pm 2.9	21.8 \pm 2.0
19 Hogenkamp, Stafleu, et al. (2012), Part A + B + C + D + E + F	81 ³		9	18	21.0 \pm 2.4	22.2 \pm 1.6
25 Julis and Mattes (2007)	47		29	18	24.0 \pm 6.3	28.3 \pm 2.6
26 Komai, et al. (2016)	10		0	10	20.6 \pm 1.9	20.0 \pm 1.3
27 Labouré, et al. (2002), Product A + B	12		12	0	21.5 \pm 2.1	22.3 \pm 2.1
29 Larsen, et al. (2016), Step 1 + 2	26					
31 Lasschuijt, et al. (2017), Part A + B	58		14	44	23.0 \pm 9.0	22.0 \pm 2.0
33 Lavin, et al. (2002)	20		10	10		23.7 \pm 3.1
34 Li, et al. (2011), Group A	16		16	0	20.8 \pm 0.8	20.1 \pm 2.0
35 Li, et al. (2011), Group B	14		14	0	20.4 \pm 0.7	30.1 \pm 3.0
36 Martens, et al. (2011)	10		10	0	21.1 \pm 3.9	22.4 \pm 1.2
37 Martin, et al. (2007), Group A	22		22	0	32.0 \pm 11.8	30.9 \pm 2.6
38 Martin, et al. (2007), Group B	26		0	26	29.6 \pm 8.8	29.4 \pm 2.9
39 Mattes and Considine (2013), Group A	30		15	15	25.7 \pm 8.4	21.2 \pm 1.3
40 Mattes and Considine (2013), Group B	30		15	15	26.5 \pm 8.4	32.7 \pm 1.6
41 McCrickerd, et al. (2017)	58		28	30	24.6 \pm 4.5	22.1 \pm 3.0
43 Mourao, et al. (2007), Product A	40		20	20	23.2 \pm 5.0	26.2 \pm 1.5
44 Mourao, et al. (2007), Product B	40		20	20	25.4 \pm 7.5	26.3 \pm 1.7
45 Mourao, et al. (2007), Product C	40		20	20	24.8 \pm 4.9	27.1 \pm 1.6
46 Park, et al. (2016), Group A	25		0	25	26.0 \pm 8.0	22.0 \pm 2.0
47 Park, et al. (2016), Group B	25		0	25	36.0 \pm 13.0	33.0 \pm 3.0
48 Smit, et al. (2011)	11		4	7		27.2 \pm 6.4
49 Spiegel, et al. (1993), Product A + B	18		0	18	28.8 \pm 9.8	26.8 \pm 7.2
51 Swoboda and Temple (2013)	44		21	23	31.1 \pm 11.5	26.2 \pm 5.2
52 Tang, et al. (2016), Step 1 + 2	38		22	16	25.2 \pm 3.4	
54 Weijzen, et al. (2008)	59		5	54	28.4	22.3
55 de Wijk, et al. (2008), Study 1	9		4	5		24.4
56 de Wijk, et al. (2008), Study 2	10		6	4		25.3
57 Zhang, et al. (2015)	12					
58 Zhu and Hollis (2014)	47		24	23	23.5 \pm 6.4	28.0 \pm 6.1
59 Zhu, et al. (2013)	21		21	0	24.0 \pm 4.6	24.8 \pm 2.7
60 Zijlstra, et al. (2011), Group A	27		6	21	36.0 \pm 14.0	21.8 \pm 1.6
61 Zijlstra, et al. (2011), Group B	27		6	21	36.0 \pm 14.0	30.5 \pm 5.7
62 Zijlstra, et al. (2010), Product A + B + C	106		45	61	24.0 \pm 7.0	21.8 \pm 1.7
65 Zijlstra, et al. (2008), Study 1	108		36	72	26.0 \pm 7.0	22.7 \pm 2.4
66 Zijlstra, et al. (2008), Study 2	49		14	35	24.0 \pm 6.0	22.2 \pm 2.3

Study ID and reference	n 1	n 2	Male	Female	Mean Age ± SD	Mean BMI ± SD
67 Zijlstra, Mars, et al. (2009)	32		12	20	22.0 ± 2.0	21.9 ± 2.2
68 Zijlstra, de Wijk, et al. (2009), Condition 1 + 2 + 3	22		8	14	21.0 ± 2.0	21.9 ± 1.5

¹ Between subjects design

² Between subjects design

³ Within subjects design; 27 participants * 3 meals per day = 81 observations

Supplementary Table 2: Meta-analysis data on appetite ratings

Study ID and reference	Category	n 1	n 2	Test food type	Fasting time (h)	Hunger units	Mean Hunger ¹ ± SD	Mean Hunger ² ± SD	Hunger p-value	DE ³ units	Mean DE ¹ ± SD	Mean DE ² ± SD	DE p-value
6 Cassady, et al. (2009)	Number of chews	13		Solid	8	mm	-12.5 ± 15.7	-22.0 ± 20.5	<0.05				
7 Ferriday, et al. (2016), Step 1	Eating rate	24		Meal	3	mm	-28.9 ± 23.4	-28.9 ± 25.3	<0.05				
9 Ferriday, et al. (2016), Step 3	Eating rate	24		Meal	3	mm	-27.2 ± 31.0	-35.5 ± 24.3	<0.05				
14 Higgs and Jones (2013)	Chewing duration	14	13 ⁴	Solid	2	mm	-55.7 ± 18.1	-45.1 ± 17.6	>0.1	mm	-47.0 ± 22.2	-45.0 ± 17.4	>0.1
15 Hogenkamp, et al. (2010), Part A	Texture	33	35 ⁵	Liquid/Solid	8	mm	-14.3 ± 15.8	-15.0 ± 16.8	>0.05	mm	-15.5 ± 16.7	-19.0 ± 15.9	>0.05
16 Hogenkamp, et al. (2010), Part B	Texture	34	35 ⁶	Liquid/Solid	8	mm	-18.3 ± 19.8	-21.7 ± 20.2	<0.05	mm	-17.5 ± 19.4	-22.2 ± 21.1	>0.05
19 Hogenkamp, Stafleu, et al. (2012), Part A	Texture	81	78 ⁷	Liquid/Solid	8	10-points	-16.4 ± 20.2	-25.7 ± 22.7	<0.0001	10-points	-9.8 ± 21.8	-15.9 ± 24.0	<0.0001
20 Hogenkamp, Stafleu, et al. (2012), Part B	Texture	81	81	Liquid/Solid	8	10-points	-10.9 ± 20.2	-15.9 ± 21.4	<0.0001	10-points	-7.3 ± 17.3	-9.3 ± 19.4	<0.0001
21 Hogenkamp, Stafleu, et al. (2012), Part C	Texture	81	81	Liquid/Solid	8	10-points	-12.3 ± 21.1	-15.7 ± 20.6	<0.0001	10-points	-7.6 ± 20.3	-10.8 ± 18.6	<0.0001
22 Hogenkamp, Stafleu, et al. (2012), Part D	Texture	81	81	Liquid/Solid	8	10-points	-18.0 ± 22.7	-22.7 ± 22.6	<0.0001	10-points	-6.5 ± 24.3	-13.6 ± 24.3	<0.0001
23 Hogenkamp, Stafleu, et al. (2012), Part E	Texture	81	80 ⁸	Liquid/Solid	8	10-points	-15.6 ± 22.5	-21.7 ± 21.2	<0.0001	10-points	-6.6 ± 21.5	-13.4 ± 21.4	<0.0001
24 Hogenkamp, Stafleu, et al. (2012), Part F	Texture	79	81 ⁹	Liquid/Solid	8	10-points	-14.6 ± 22.2	-19.5 ± 20.6	<0.0001	10-points	-9.2 ± 20.1	-11.4 ± 20.1	<0.0001
26 Komai, et al. (2016)	Number of chews	10		Meal	10	mm	-64.6 ± 30.9	-67.1 ± 30.9	0.959				
27 Labouré, et al. (2002), Product A	Texture	12		Liquid/Semi-solid	5.5	mm	-62.3 ± 27.2	-71.4 ± 22.2	>0.05				
28 Labouré, et al. (2002), Product B	Texture	12		Liquid/Solid	5.5	mm	-54.3 ± 11.7	-72.8 ± 22.2	>0.05				
29 Larsen, et al. (2016), Step 1	Texture complexity	26		Solid	3	mm	-8.7 ± 29.7	-11.9 ± 32.0	>0.05	mm	-8.1 ± 23.8	-10.8 ± 32.1	<0.05
33 Lavin, et al. (2002)	Texture	20		Liquid/Solid	2.5	mm	-7.0 ± 28.3	-2.0 ± 33.9	0.35				
36 Martens, et al. (2011)	Texture	10		Liquid/Solid	3	mm	-44.1 ± 28.3	-51.4 ± 20.9	>0.05	mm	-38.6 ± 17.5	-54.0 ± 15.6	>0.05
52 Tang, et al. (2016), Step 1	Texture complexity	38		Solid	3	mm	-3.7 ± 24.9	-5.5 ± 26.9	>0.05	mm	-5.4 ± 25.3	-7.0 ± 28.5	>0.05

Study ID and reference	Category	n 1	n 2	Test food type	Fasting time (h)	Hunger units	Mean Hunger ¹ ± SD	Mean Hunger ² ± SD	Hunger p-value	DE ³ units	Mean	Mean	DE p-value
											DE ¹ ± SD	DE ² ± SD	
57 Zhang, et al. (2015)	Texture	12		Liquid/Solid	2.5	mm	-9.0 ± 10.4	-7.5 ± 8.0	>0.05	mm	-5.0 ± 8.7	-9.2 ± 8.7	>0.05
59 Zhu, et al. (2013)	Number of chews	21		Meal	8	mm	-23.5 ± 20.0	-25.0 ± 23.9	0.009	mm	-22.6 ± 20.0	-25.0 ± 20.0	0.002
67 Zijlstra, Mars, et al. (2009)	Texture	32		Liquid/Solid	12	10-points	-15.0 ± 23.0	-21.3 ± 22.5	>0.05	10-points	-10.8 ± 25.9	-19.2 ± 25.8	>0.05

¹ Large bite size, fast eating rate, low number of chews, short oral residence time and soft texture conditions

² Small bite size, slow eating rate, high number of chews, long oral residence time and hard texture conditions

³ DE: Desire to Eat

⁴ Between subjects design

⁵ Between subjects design; decreased sample size in n1 due to missing values

⁶ Between subjects design

⁷ Within subjects design, 27 participants * 3 meals per day = 81 observations, decreased sample size in n2 due to missing values

⁸ Within subjects design, 27 participants * 3 meals per day = 81 observations, decreased sample size in n2 due to missing values

⁹ Within subjects design, 27 participants * 3 meals per day = 81 observations, decreased sample size in n1 due to missing values

Supplementary Table 3: Meta-analysis data on food intake

Study ID and reference	Category	n 1	n 2	Mean Food intake ¹ ± SD	Mean Food intake ² ± SD	Intake p-value
1 Andrade, et al. (2008)	Eating rate	30		645.7 ± 155.9	579.0 ± 154.7	<0.01
2 Bolhuis, et al. (2011), Part A	Eating rate	55		66.0 ± 33.6	90.0 ± 39.6	<0.05
3 Bolhuis, et al. (2011), Part B	Eating rate	55		60.0 ± 30.0	82.8 ± 34.8	<0.05
4 Bolhuis, et al. (2014), Step 1	Texture	50		737.0 ± 155.0	644.0 ± 173.0	<0.001
5 Bolhuis, et al. (2014), Step 2	Texture	50		565.5 ± 179.4	540.2 ± 170.1	0.16
7 Ferriday, et al. (2016), Step 1	Eating rate	24		640.8 ± 321.4	529.8 ± 238.5	0.004
8 Ferriday, et al. (2016), Step 2	Eating rate	24		338.5 ± 190.6	297.8 ± 167.9	0.004
9 Ferriday, et al. (2016), Step 3	Eating rate	24		196.3 ± 190.0	223.3 ± 189.6	0.35
10 Ferriday, et al. (2016), Step 4	Eating rate	24		389.3 ± 223.2	423.2 ± 233.0	0.35
11 Hetherington and Boyland (2007), Part A	Chewing gum	60		461.3 ± 199.1	407.1 ± 217.1	<0.05
12 Hetherington and Boyland (2007), Part B	Chewing gum	60		164.8 ± 198.3	351.0 ± 176.8	>0.05
13 Hetherington and Regan (2011)	Chewing gum	60		247.5 ± 106.9	222.4 ± 108.4	0.029
14 Higgs and Jones (2013)	Chewing duration	14	13 ³	270.5 ± 121.5	127.6 ± 97.8	0.01
15 Hogenkamp, et al. (2010), Part A + B	Texture	68	70 ⁴	555.9 ± 236.5	431.6 ± 186.0	0.03
17 Hogenkamp, Mars, et al. (2012), Part A	Texture	53		374.1 ± 198.5	274.4 ± 119.9	<0.0001
18 Hogenkamp, Mars, et al. (2012), Part B	Texture	53		458.3 ± 171.3	369.3 ± 165.5	<0.0001
19 Hogenkamp, Stafleu, et al. (2012), Part A	Texture	81		1767.0 ± 581.0	1720.0 ± 583.0	0.56
20 Hogenkamp, Stafleu, et al. (2012), Part B	Texture	81		1886.0 ± 465.0	1850.0 ± 546.0	0.56
21 Hogenkamp, Stafleu, et al. (2012), Part C	Texture	81		2016.0 ± 582.0	1941.0 ± 560.0	0.56
22 Hogenkamp, Stafleu, et al. (2012), Part D	Texture	81		1549.0 ± 427.0	1496.0 ± 438.0	0.56
23 Hogenkamp, Stafleu, et al. (2012), Part E	Texture	81		1537.0 ± 418.0	1554.0 ± 460.0	0.56
24 Hogenkamp, Stafleu, et al. (2012), Part F	Texture	81		1589.0 ± 448.0	1588.0 ± 407.0	0.56
25 Julis and Mattes (2007)	Chewing gum	47		1415.0 ± 747.3	1330.0 ± 822.7	>0.05
27 Labouré, et al. (2002), Product A	Texture	12		776.9 ± 299.6	790.3 ± 204.4	>0.05
28 Labouré, et al. (2002), Product B	Texture	12		939.6 ± 301.2	703.6 ± 376.6	>0.05
29 Larsen, et al. (2016), Step 1	Texture complexity	26		982.4 ± 445.6	622.4 ± 302.6	<0.01
30 Larsen, et al. (2016), Step 2	Texture complexity	26		377.8 ± 197.4	292.0 ± 175.6	0.08
31 Lasschuijt, et al. (2017), Part A	Texture	58		75.9 ± 21.7	54.1 ± 22.1	<0.001
32 Lasschuijt, et al. (2017), Part B	Texture	58		70.6 ± 21.7	51.7 ± 22.1	<0.001
33 Lavin, et al. (2002)	Texture	20		884.4 ± 209.4	766.6 ± 222.2	<0.05
34 Li, et al. (2011), Group A	Number of chews	16		555.0 ± 111.0	477.8 ± 72.4	0.021
35 Li, et al. (2011), Group B	Number of chews	14		695.0 ± 127.9	625.0 ± 106.2	0.021
37 Martin, et al. (2007), Group A	Eating rate	22		1020.0 ± 248.0	918.0 ± 225.0	<0.05
38 Martin, et al. (2007), Group B	Eating rate	26		588.0 ± 212.0	585.0 ± 216.0	>0.05
39 Mattes and Considine (2013), Group A	Chewing gum	30		2009.2 ± 414.6	1879.2 ± 452.4	0.056
40 Mattes and Considine (2013), Group B	Chewing gum	30		2146.8 ± 452.4	2339.8 ± 452.4	0.059
41 McCrickerd, et al. (2017), Part A	Texture	58		300.0 ± 84.5	271.6 ± 72.3	<0.001
42 McCrickerd, et al. (2017), Part B	Texture	58		546.3 ± 216.3	483.9 ± 204.1	<0.001
43 Mourao, et al. (2007), Product A	Texture	40		1915.0 ± 815.9	1665.0 ± 638.8	0.03
44 Mourao, et al. (2007), Product B	Texture	40		1970.0 ± 619.8	1752.0 ± 619.8	0.026

Study ID and reference	Category	n 1	n 2	Mean Food intake ¹ ± SD	Mean Food intake ² ± SD	Intake p-value
45 Mourao, et al. (2007), Product C	Texture	40		2517.0 ± 1138.4	2116.0 ± 695.7	0.016
46 Park, et al. (2016), Group A	Chewing gum	25		563.0 ± 270.0	511.0 ± 270.0	>0.05
47 Park, et al. (2016), Group B	Chewing gum	25		676.0 ± 270.0	613.0 ± 270.0	>0.05
48 Smit, et al. (2011)	Number of chews	11		702.2 ± 125.0	612.8 ± 111.9	0.006
49 Spiegel, et al. (1993), Product A	Bite size	18		770.0 ± 237.7	784.0 ± 297.1	>0.05
50 Spiegel, et al. (1993), Product B	Bite size	18		883.3 ± 283.0	833.3 ± 283.0	>0.05
51 Swoboda and Temple (2013)	Chewing gum	44		254.5 ± 150.6	227.3 ± 195.7	>0.05
52 Tang, et al. (2016), Step 1	Texture complexity	38		793.0 ± 246.7	696.9 ± 296.1	<0.01
53 Tang, et al. (2016), Step 2	Texture complexity	38		235.2 ± 73.1	246.8 ± 90.6	0.839
54 Weijzen, et al. (2008)	Bite size	59		192.0 ± 132.1	169.1 ± 128.6	0.02
55 de Wijk, et al. (2008), Study 1	Texture	9		402.5 ± 213.5	222.8 ± 27.1	0.003
57 Zhang, et al. (2015)	Texture	12		830.0 ± 405.3	809.0 ± 426.1	>0.05
58 Zhu and Hollis (2014)	Number of chews	47		760.0 ± 371.1	647.1 ± 322.6	0.001
59 Zhu, et al. (2013)	Number of chews	21		1098.3 ± 546.0	1117.6 ± 668.9	0.851
60 Zijlstra, et al. (2011), Group A	Texture	27		572.5 ± 270.0	376.5 ± 198.3	<0.05
61 Zijlstra, et al. (2011), Group B	Texture	27		600.0 ± 251.3	369.8 ± 166.2	<0.05
62 Zijlstra, et al. (2010), Product A	Texture	106		406.6 ± 323.8	393.7 ± 321.9	>0.05
63 Zijlstra, et al. (2010), Product B	Texture	106		174.4 ± 113.2	164.8 ± 112.3	>0.05
64 Zijlstra, et al. (2010), Product C	Texture	106		592.0 ± 372.6	565.8 ± 340.3	>0.05
65 Zijlstra, et al. (2008), Study 1	Texture	108		788.5 ± 386.0	567.9 ± 312.1	<0.0001
66 Zijlstra, et al. (2008), Study 2	Eating rate	49		226.8 ± 122.4	176.6 ± 88.3	0.01
67 Zijlstra, Mars, et al. (2009)	Texture	32		394.8 ± 212.9	371.5 ± 178.0	>0.05
68 Zijlstra, de Wijk, et al. (2009), Condition 1	Chewing duration	22		427.7 ± 185.2	416.4 ± 189.9	0.0008
69 Zijlstra, de Wijk, et al. (2009), Condition 2	Bite size	22		406.1 ± 153.2	294.2 ± 159.8	<0.0001
70 Zijlstra, de Wijk, et al. (2009), Condition 3	Bite size	22		447.4 ± 165.4	359.1 ± 185.2	<0.0001

¹ Large bite size, fast eating rate, low number of chews, short oral residence time, soft texture and no chewing gum conditions

² Small bite size, slow eating rate, high number of chews, long oral residence time, hard texture and chewing gum conditions

³ Between subjects design

⁴ Between subjects design; n1: 34 participants * 2 energy density products = 68 observations, n2: 35 participants * 2 energy density products = 70 observations

Supplementary Table 4: Characteristics of studies involving lubrication measures

Reference	Participants			Study information			Outcomes		
	n	Age	BMI status	Study design	Test food	Test procedure	Lubrication measure	Effect appetite	Effect food intake
Gavião, et al. (2004)	16	35 ± 13	NA	Randomized, 3-arm, within subjects design	Parafilm, Melba toast with and without margarine, breakfast cake and cheese	Parafilm and 3 different types of food products were chewed and expectorated in duplicate, and salivary flow rate was measured	Flow rate significantly increased due to mechanical stimulation by Parafilm and by food. Dry foods had longer oral exposure time than more moist products, while flow rate was similar. Toast with margarine reduced chewing duration and number of chewing cycles	NA	NA
Joyner, et al. (2014)	7	NA	NA	Randomized, 16-arm, within subjects design	Acid milk gels containing thickeners	16 acid milk gel samples, tested for sensory texture attributes in QDA, as well as instrumental rheological and tribological properties	Starch had an impact on friction behavior of acid milk gels, and addition of artificial saliva resulted in a change of frictional behavior across the entire range of sliding speeds	NA	NA
Lett, Norton, et al. (2016)	34	Range: 18-37	22.7 ± 1.6	Randomized, 2-arm, within subjects design	Emulsions with different droplet size	Fixed preload emulsions with a droplet size of 2 or 50 µm, followed by an ad libitum pasta lunch	Rheological and lubrication properties for the two emulsions were comparable (results not published at this time)	Yes, ↓ hunger after 2 µm compared to 50 µm preload (however fullness not different)	Yes, food intake after 2 µm preload ↓ than after the 50 µm preload
McCrickerd, et al. (2014)	48	20.8 ± 5.3	NW	Randomized, 4-arm, within subjects design	Fruit drinks,, containing thickeners and creamy flavorings	Ad libitum intake of 4 iso-energetic fruit drinks varying in texture (thin vs thick) and creamy flavor (low vs high creaminess)	Both instrumental viscosity and lubrication (Stribeck) properties were measured, with the thick drinks being more viscous and more lubricating. The creamy flavor additions did not affect the physical texture of the drinks (both viscosity and lubrication)	No difference in appetite ratings	Yes, for females consumption of the thick drink ↓ than the thin drink. However, no differences found in food intake for males, or due to creamy flavor, regardless of gender

Morell, et al. (2014)	106	Range: 18-61	NA	Randomized, 4-arm, within subjects design	Milkshakes, containing thickeners	Sip-test of 4 milkshakes with consumer panel using CATA questionnaires	The swollen starch granules in modified starch disintegrated in presence of artificial saliva	Yes, modified starch had the highest satiety expectation score, and native starch, guar gum and λ -carrageenan the lowest as linked to their sensory creamy sensations when entering the mouth	NA
Morell, et al. (2015)	121	NA	NA	Randomized, 6-arm, within subjects design	Yoghurts, containing protein and thickeners	Spoonful test of 6 yoghurts with consumer panel	Physically modified starch granules remain unaltered in presence of α -amylase from artificial saliva leading to a thick, dense and creamy yoghurt that could lead to a longer oro-sensory exposure	Yes, samples which were perceived as thicker and denser were perceived as having a higher satiating capacity	NA