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Application of food texture to moderate oral processing behaviors and energy intake

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ABSTRACT

Background: Many studies have shown that changes in food textures are able to reduce food intake via longer oral processing and slower eating rate, without a resultant decrease in food liking or post-meal fullness.
Scope and approach: The current paper consolidates findings from to date and summarizes current knowledge on (i) how specific food textures influence oral processing, and (ii) how oral processing influence eating rate and food intake. An overview is presented of potential food texture based applications for future opportunities to moderate energy intake.
Key findings and conclusions: Oral processing characteristics that particularly influence both eating rate and food intake are bite sizes and chewing behaviour. Increasing the hardness and elasticity of solid foods has been shown to increase chews per bite and decrease bite sizes to reduce eating rate and food intake. By contrast, increasing lubrication can stimulate faster eating rates by reducing the chews per bite required to agglomerate a swallowable bolus. The shape and size of foods can be designed to either directly influence the bite sizes or to manipulate surface area and moisture uptake to influence bolus formation and through this, eating rate and food intake. For semi-solid foods, manipulations in viscosity and particle sizes have been shown to affect eating rate and intake. The current evidence supports a new and largely underutilised opportunity to apply texture manipulations together with decreasing energy densities to moderate the flow of calories through our diets and to support better long-term energy intake control.

1. Introduction

Rising rates of diet based, non-communicable diseases are negatively related to both physical and mental health. Increased energy consumption during meals or snacks is associated with sustained positive energy balance over time, and a higher prevalence of overweight and obesity. In response to the public health challenges associated with the rise in non-communicable disease, concerted efforts are being made by governments and food producers to reformulate products to reduce energy density, and enhance nutrient density (Rimmer, 2018). This has traditionally been focused on reducing public health sensitive nutrients such as salt, sugar and fat and limiting portion sizes. However, beyond 'what' is consumed, there is emerging evidence that shows 'how' a food is eaten can impact the extent to which it is consumed, and the satisfaction we derive per kcal consumed. Faster onset of satiation will facilitate acceptance of smaller portions (Bolhuis, Forde, et al., 2014), and enhanced satiety per kcal consumed can support reduced intakes of salt, sugar and energy within a meal and over time. In parallel, age related changes in masticatory function and physiological reductions in appetite, increasingly challenge older consumers and vulnerable populations to sustain sufficient food intake and nutritional adequacy (Ketel, de Wijk, de Graaf, & Stieger, 2020).

The amount of energy intake within a snack or meal, (i.e., ad libitum energy intake), is determined by individual characteristics including habitual eating behaviours, appetite need-state, and subjective palatability (Bobroff & Kissileff, 1986; de Castro, 1988; De Graaf, De Jong, & Lambers, 1999). In addition, food properties can influence ad libitum energy intake, including energy density, ease of consumption and sensory factors that stimulate the onset of satiation (Chambers, McCrickerd, & Yeomans, 2015; Hetherington, 1996; Rolls, 2009). In recent years

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accumulating evidence from human feeding trials point to a new approach to understanding how food sensory characteristics can moderate ad libitum energy intake within meals or snacks (Boesveldt & de Graaf, 2017; McCrickerd & Forde, 2016). Increasing evidence shows that particularly the energy intake rate (EIR; kcal/min), the product of eating rate (g/min) and energy density, is a strong determinant of ad libitum energy intake (Forde, Mars, & de Graaf, 2020; van den Boer, Werts, Siebelink, de Graaf, & Mars, 2017). Foods textural properties are the major determinants of its eating rate (g/min), in addition to minor effects of flavour intensity (Bolhuis, Lakemond, de Wijk, Luning, & de Graaf, 2011), and as a function of differences in individual characteristics such as liking, familiarity, oral physiology, age, and gender (Engelen, Fontijn-Tekamp, & van der Bilt, 2005; Ketel et al., 2019). In addition to curtailing intake, food texture can also be tailored to create new opportunities to adapt food structures to enhance optimum energy and nutrient intakes among vulnerable populations. Food textures that supports high eating rates by reducing the need for extensive chewing and lubrication, can be used to optimize food appeal and intake among vulnerable populations of older consumers or those receiving palliative care.

The current paper focusses on how a food's textural properties can be used to influence oral processing behaviours and energy intake, and synthesises the evidence across different sources and disciplines. The influence of food texture on intake behaviour has been studied widely by scientists from different disciplines from food physics and oral processing on the one hand and by scientist specialised in nutrition and eating behaviours on the other. The current review aims to bridge these disciplines to summarise the available evidence on how specific food textures influence oral processing and energy intake. An overview will be presented of potential applications for future opportunities to moderate energy intake.

2. Energy intake rate determines ad libitum energy intake

Both energy density (kcal/g) and eating rate (g/min) have been shown to have strong independent and combined effect on energy intake, and the product of these factors, the EIR (kcal/min), is considered a powerful determinant of ad libitum energy intake (Forde et al., 2020; Hall et al., 2019; van den Boer et al., 2017). Humans have a poor ability to adjust for variations in energy density, with many studies showing a similar weight/volume of foods are consumed across variants of low and high energy density food (Bell, Castellanos, Pelkman, Thorwart, & Rolls, 1998; Bolhuis, Costanzo, Newman, & Keast, 2016; Kral & Rolls, 2004; Tey, Chia, & Forde, 2016). Ad libitum consumption from pasta meals with high and low energy dense sauce showed 60% higher energy intake in the high energy dense version, but no differences in intake in grams (Bolhuis et al., 2016). The increase in energy intake from higher energy densities has been demonstrated across both sexes, among adults and children, across body weight classes, across different mixes of macronutrients, and at a single meal and whole-diet level, highlighting the robust nature of this relationship (Rolls, 2009). Importantly, overconsumption of calories are not likely to be compensated for in the next eating occasion and are a risk factor for sustained positive energy balance and weight gain (Hall et al., 2019; Rolls, 2009; Rolls, Roe, & Meengs, 2007; Tey et al., 2016). Conversely, reducing the intake of higher energy dense foods, and increasing the consumption of low energy dense foods leads to sustained lower energy intake and body weights (Vadiveloo, Parker, & Raynor, 2018).

Slowing down eating rate (g/min) to moderate food intake by chewing thoroughly was advocated by Fletcher over one hundred years ago in the early 19th century. Since then, many studies have shown that eating rate and chews per bite influence food intake, yet surprisingly this approach has not resulted in wide-spread application of food texture in food product designs to reduce the risk of overconsumption. A meta-analysis of self-reported eating rates and body weight shows a consistent positive relationship between faster eating rates and higher BMI in both cross-sectional and prospective longitudinal studies (Berkowitz et al., 2010; Ohkuma et al., 2015; Tanihara et al., 2011). In a recent cross sectional study, those reporting higher eating rates were shown to consume 105 kcal/day more, had an average of 5 kg greater body weight, 1.3 kg/m^2 higher BMI, and larger waist-circumference (Teo, van Dam, Whitton, Tan, & Forde, 2020). Individual differences in eating rate are also likely dependent on a range of physiological factors such as fat free mass and basal metabolic rate (Henry, Ponnalagu, Bi, & Forde, 2018), gender and age (Aguayo-Mendoza et al., 2020; Ketel et al., 2020). Similarly, differences in the manner of consumption such as use of utensils or drinking via straw or directly from a glass, can also determine a products eating rate and influence the amount of food intake (Bolhuis & Keast, 2016; Hogenkamp, Mars, Stafleu, & de Graaf, 2010; Sun, Ranawana, Tan, Quek, & Henry, 2015).

Evidence that faster eating rates are associated with higher food intake was summarised in a systematic review and meta-analysis across 22 studies that manipulated eating rate using verbal or food textural properties (Robinson et al., 2014). A medium to small significant effect size was observed showing that individuals in the fast condition eat more than in the slow condition. From these 22 studies, seven studies manipulated eating rate by textural changes, which included food in softer (blended, mashed) or harder versions, and with lower and higher viscosities. Effect sizes and explanations for how textural manipulations affect eating rate and food intake are covered in the following sections. Similarly, a separate systematic review and meta-analysis demonstrated that increasing the chews per bite, reduced food intake and enhanced satiety, demonstrating that slowing down the rate of intake can significantly reduce intake and increase post-meal fullness (Miquel-Kergoat, Azais-Braesco, Burton-Freeman, & Hetherington, 2015). In some studies in the meta-analysis, gum was chewed before meals or snacks, while in otherstudies changes in food textures were used to enhance chewing behaviour, and others used the same texture but instructed individuals to change the number of chews per bite. Ten out of 16 studies found that chewing reduced food intake, while three of the five studies showed that increasing the number of chews per bite increased relevant gut hormones, and two showed an enhanced subjective satiety.

Importantly, as with energy density, for acute texture based reductions in energy intake at one meal, there appears to be negligible energy compensation at the following meal. In one cross-over feeding trial, participants received harder and softer versions of a lunchtime meal to with significant reductions of 13% in ad libitum energy intake for the harder meal, that were not compensated for during later snacking or evening meal intake. This produced a net 11% reduction in energy intake for a single day (Bolhuis, Lakemond, de Wijk, Luning, & de Graaf, 2014). In this trial, the harder lunch consisted of hard version of hamburger buns and 'harder' salad (rice and raw vegetables) and the softer lunch consisted of soft hamburger buns and 'soft' salad (risotto and boiled vegetables) (Table 1). Verbal and visual instructions to slow eating rate have previously been shown to be effective in reducing energy intake by using smaller utensils, providing instructions to increase chews or decreasing bite frequencies, or combinations of those (Andrade, Greene, & Melanson, 2008; Andrade, Kresge, Teixeira, Baptista, & Melanson, 2012; Scisco, Muth, Dong, & Hoover, 2011). In addition, two clinical trials have demonstrated significant reductions in body mass as a result of sustained reductions in energy intake by targeting eating rates using a device to prompt slower eating speeds (Ford et al., 2010; Galhardo et al., 2012).

However, most studies to date have been conducted on healthy and generally young individuals that showed effect of eating rate on food intake. Not all consumers will be equally responsive to texture based eating rate interventions, and this may be more or less effective when taking into account one's initial eating rate or oral processing behaviours. Indeed, some studies show individuals that did not reduce their food intake when eating rate was slowed down, which may depend on the individual's microstructural pattern of eating behaviour (Zandian, Ioakimidis, Bergh, Brodin, & Sodersten, 2009), or differences in body

Table 1

Effect sizes of studies where a texture manipulations were applied to reduce eating rate and ad libitum intake. Test foods were matched on energy density and similar in palatability or corrected accordingly.

Type of manipulation	Slow/Fast condition, Difference perceived/ instrumental	Manner of consumption	Eating rate (g/min) (slow/fast)	Ad libitum intake (g) (slow/fast)	Reference
Viscosity					
Chocolate drink	Semi solid/Liquid 'Thickness' (10-point scale) Semi solid: 5.5 Liquid: 1.9 Viscosity (shear rate 50/s at 5 °C) Semi solid: 788 mPa/s Liquid: 85 mPa/s	Straw, carton container	37%	34%	Zijlstra et al. (2008)
Cheese dip	Thick/Thin Viscosity (shear rate 1/s at 20 °C) Thick: 124 Pa/s Thin: 55 Pa/s	Spooned on crackers	–	–	van Eck et al. (2020)
Porridge	Thick/Thin 'Thickness' (VAS[a] 0–100) Thick: 79 Thin: 15	Spoon, bowl	41%	12%	McCrickerd et al. (2017)
Yoghurt with granola	Thick/Thin Viscosity (shear rate 1/s 25 °C) Thick: 69 Pa/s Thin: 38 Pa/s	Spoon, bowl	–	–	Mosca et al. (2019)
Custard	Semi solid/Liquid 'Thickness' (VAS 0–100)Semi solid: 85 Liquid: 15	Spoon, bowl	23%	25%	Hogenkamp, Mars, Stafleu, and de Graaf (2012)
Yoghurt	Semi solid/Liquid 'Thickness' (VAS 0–100) Semi solid: 66 Liquid:19	Spoon, bowl	–	–	Hogenkamp et al. (2010)
Shape					
Chocolate snacks	Nibbles/Bar Nibbles: 1.5 g, 2.5 × 1.5 × 1.0 cm. Bar: 16 g 9 × 4 × 1 cm	Served on a plate	16%	12%	Weijzen et al. (2008)
Shape cracker	Finger form/Flat form (equal weight) Finger form: 60 × 10 × 10 mm; surface area 2600 mm^2 Flat form: 40 × 40 × 3 mm; surface area 3680 mm^2	Consumed with cheese dips	15%	8% (trend)	van Eck et al. (2020)
Particles					
Granola size in yoghurt	Small/Large (equal w/w %) Small: 6 mm Large: 12 mm	Spoon, bowl	7%	5%	Mosca et al. (2019)
Hardness					
Luncheon meat	Hard/Soft 'Firmness' (VAS 0–100) Hard:67 Soft: 58	Served in pieces in a container	16%	6% (n.s)	Zijlstra, Mars, Stafleu, and de Graaf (2010)
Candy	Hard/Soft 'Firmness' (VAS 0–100) Hard:53 Soft: 56	Served in pieces in a container	-no effect	- no effect	Zijlstra et al. (2010)
Meat replacer	Hard/Soft 'Firmness' (VAS 0–100) Hard:62 Soft: 62	Served in pieces in a container	- no effect	- no effect	Zijlstra et al. (2010)
Meals (Carrot, Potato, Meat)	Whole foods/Mashed foods	Utensils, served on a plate	17%	Total: 6% (n.s) Carrots: 13% Potato: no effect Meat: no effect	Forde et al. (2013b)
Hamburger	Hard buns/Soft buns 'Hardness' (VAS 0–100): Hard: 73 Soft: 26	Served on a plate	29%	9%	Bolhuis, Forde, et al. (2014)

(*continued on next page*)

Table 1 (*continued*)

Type of manipulation	Slow/Fast condition, Difference perceived/ instrumental	Manner of consumption	Eating rate (g/min) (slow/fast)	Ad libitum intake (g) (slow/fast)	Reference
Salad	Hard/Soft 'Hardness' (VAS 0–100): Hard:54 Soft: 30	Spoon	58%	17%	Bolhuis, Forde, et al. (2014)
Gel-based model foods	Hard/Soft 'Hardness' (VAS 0–100): Hard:67 Soft: 22 Fracture stress : Hard: 355 kPa Soft: 46 kPa Fracture strain : Hard: 69 % Soft: 57 %	Served in pieces in bowl, consumed with fork	42%	21%	Lasschuijt et al. (2017)

[a] Visual Analogue Scale (VAS) of 100 units.

weight or energy needs (Shah et al., 2014). Reducing energy intake using textural changes may also be less useful for elderly who do not have optimal oral health. Although the role of food texture in moderating eating rate and food intake has been clearly demonstrated, future research is now needed to test whether the effect of food texture on eating rate is consistent across different consumer groups. Moreover, to date, human trials are lacking that investigate the longer term effects of food texture on energy intake and body weight.

3. Food texture influences eating rate and energy intake

In both meta-analyses cited in the previous section, several of the studies to date have applied differences in food textures to moderate eating rate. A significant advantage of using food textures to slow eating rate is that texture leads to a natural adjustment to food oral processing behaviours at an individual level, which can reduce the rate of eating and for the most part, these changes have been implemented without a loss of sensory appeal of decreased post-meal satisfaction (Ferriday et al., 2016). In this regard, texture manipulation affords an opportunity to moderate oral processing behaviours without relying on external devices, verbal prompts or specific instructions or restrictions to guide behaviours.

Table 1 summarizes effect sizes of texture manipulations on eating rate and ad libitum intake. Smaller manipulations to food texture tend to have a weaker impact on oral processing behaviours and eating rates, and the quantity of food consumed, whereas larger manipulations may completely alter the food form (e.g., from liquid to semi solid) and have a significantly larger effect on the rate of eating and food intake. The findings summarised in Table 1 indicate that eating rate needs to be manipulated substantially to influence ad libitum energy intake. The extent to which eating rate is reduced tends to be larger than the impact on ad libitum intake. A general guideline that has been proposed based on previous research with texture based differences is to achieve a minimum 20% reduction in eating rate to initiate a 10–15% reduction in energy intake (Forde, 2018). It is noteworthy that there is wide-variation in effect sizes across different texture manipulations for both eating rate and ad libitum intake. This is possibly a consequence of the impact different food textures have on specific aspects of oral processing, and by modifying these specific behaviours it is possible to reduce eating rate and ad libitum food intake to a greater or lesser extent. These specific aspects will be discussed in more detail in the following section.

4. The impact of texture on food oral processing behaviour

Food oral processing behaviour includes all processes that transform food into a bolus that can be safely swallowed. Hutchings and lillford (1988) hypothesized a food 'breakdown pathway' along three dimensions, degree of structure, degree of lubrication, and time. Solid foods need to be chewed to reduce structure, fragmented into particles that are then lubricated with saliva to a point where fragments agglomerate and bind together as a coherent bolus, which exhibits viscoelastic behaviour, and can be pushed to the back of the oral cavity using tongue movements for swallowing (Fig. 1) (Witt & Stokes, 2015). Saliva secretion triggered by chewing facilitates the softening, binding and lubrication needed during food breakdown, to form a cohesive bolus that maintains its integrity while being deformed during swallowing, and subsequent peristalsis (Mosca & Chen, 2017).

Foods differ considerably in their requirement for lubrication from saliva during mastication, and this is dependent on the initial moisture and dry matter content of the food and its fracture and absorption properties. For example, bread requires approximately 5 times more saliva to form a swallowable bolus compared to cooked pasta. Saliva secretion is triggered by chewing together with gustatory and olfactory stimulation. The rate of saliva uptake is strongly influenced by the available surface area and absorption properties of the food bolus (Mosca & Chen, 2017). Therefore, a food that requires a lot of lubrication will increase the number of masticatory cycles to both increase the bolus particle surface area and moisten and lubricate the bolus fully, and this in turn will naturally slow the rate of consumption. As saliva production is an autonomic process that is not under direct conscious control, we typically adjust our bite size and chewing behaviour to ensure the rate of food structure breakdown and lubrication is aligned with the rate of saliva production and uptake. This illustrates how all three dimensions of the breakdown path, (structure, lubrication and time), interact dynamically to reduce or increase the rate of consumption (Fig. 2). In addition to food texture, individual characteristics such as saliva composition and flow rate, bite force and tongue pressure are likely to impact oral processing behaviour and influence the extent to which texture moderates eating rate and food intake.

Large textural differences exist between different food forms from liquids to semi solids and solids, with distinct differences in the oral processing behaviours observed during consumption. Liquids are rapidly transported from the front of the mouth to the back to be swallowed, requiring little oral processing. Semi-solids require some movement by the tongue, cheeks and palate to position the food at the back of the oral cavity for safe swallows. By contrast, solid foods require extensive oral processing and need to be broken down in to smaller particles, lubricated with saliva until particles can agglomerate to form a viscoelastic bolus that can be safely swallowed. These variations in oral processing behaviours result in large differences in eating rate, with liquids being significantly faster than semi-solids and solids. Average eating rates for solids have been reported between 10 and 120 g/min, and up to 600 g/min for semi solids and liquids (Forde, Leong, Chia-Ming, & McCrickerd, 2017; van den Boer et al., 2017; Viskaal-van Dongen, Kok, & de Graaf, 2011).

Food texture is defined as "all the mechanical, geometrical and surface attributes of a product perceptible by mechanical, tactile, or

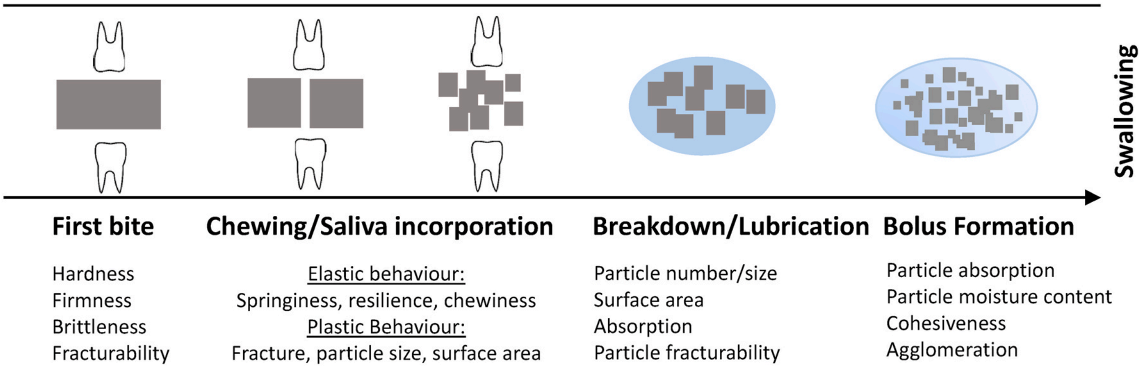

Fig. 1. Illustration of subsequent stages of food breakdown from first bite until swallowing.

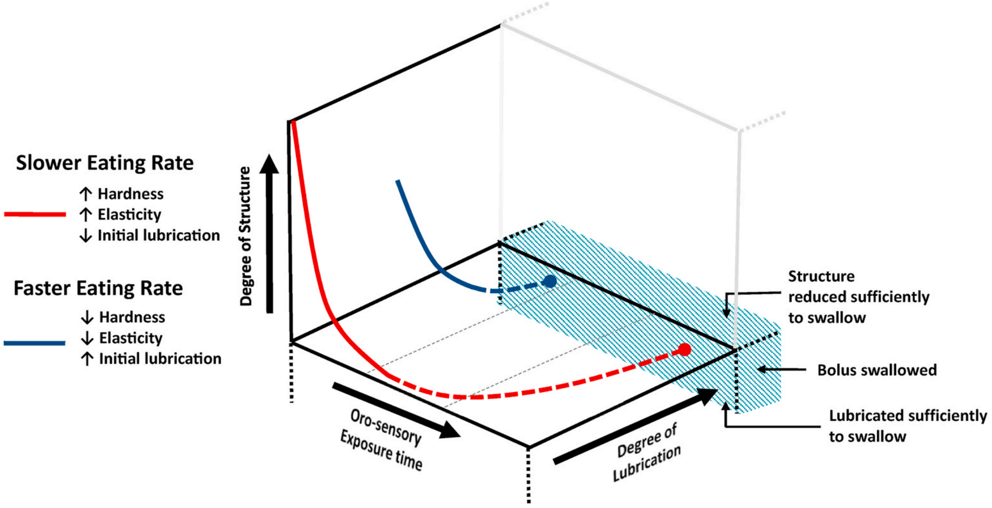

Fig. 2. Food oral breakdown pathway (Adapted from Hutchings and lillford, 1988)) illustrating faster and slower eating in response to changes in elasticity, hardness and lubrication. In this hypothetical example, the food lower in hardness and elasticity and higher in initial lubrication is processed more quickly into a bolus that is safe to swallow which result in a faster eating rate.

visual and auditory receptors" (International Standards Organization, ISO, 1994). However, texture is not a finite or one dimensional food property, but is multidimensional and dynamic in nature, as it changes rapidly in response to the deformation forces imposed during mastication. In this regard, a truly integrated and dynamic representation of texture cannot be adequately measured using simple instrumental approaches. Textural parameters can be described in terms of their bulk properties, surface-related properties and geometrical properties, and each can have a distinct influence oral processing behaviors. Bulk properties of semi-solid foods, such as viscosity, are dominant at the beginning of oral processing, whereas surface-related properties, such as friction, tend to be more important in subsequent stages of oral processing when the fluid film between the tongue and palate becomes thinner. Geometrical properties, like size and shape, influence oral processing both at initial and later masticatory stages (Stokes, Boehm, & Baier, 2013).

Bulk, surface, and geometrical properties influence oral processing behaviour characteristics such as sip or bite size, number of chews per bite, and oro-sensory exposure time (OSE, i.e., oral residence, transit time, duration from ingestion to swallowing). These bulk, surface, and geometrical properties have been shown to directly impact oral processing behaviors and the rate and extent of energy intake during consumption, as summarised below.

5. How oral processing behaviour influences ad libitum intake

The mechanism of *how* slowing down eating rate reduces ad libitum intake is not fully understood, however some mechanisms are proposed. Chewing may be a 'satiation cue' independently of its effect on eating rate, and it is possible there is dynamic feedback from oral and mechano-receptors in the oral cavity that help promote a faster onset of feelings of fullness (Hollis, 2018). In addition to chewing, longer OSE is associated with enhanced taste exposure, which in turn promotes faster onset of satiation. Experimental food intake studies have shown that increasing OSE while keeping the eating rate constant (g/min) leads to significant decreases in food intake (Bolhuis et al., 2011; Bolhuis, Lakemond, de Wijk, Luning, & de Graaf, 2013; Bolhuis, Lakemond, et al., 2014; Weijzen, Smeets, & de Graaf, 2009). This may also explain why caloric beverages which are ingested quickly and with minimal taste exposure, may promote greater intake and lead to sustained positive energy balance associated with higher body weights (Malik, Schulze, & Hu, 2006). The sense of taste has been described as a 'nutrient sensor' (Boesveldt & de Graaf, 2017) responsible for detecting the nutrient and energy content of the food being consumed, informing our expectations of fullness (Forde, Almiron-Roig, & Brunstrom, 2015), and oral-metering of food intake during consumption (Spetter, Mars, Viergever, de Graaf, & Smeets, 2014).

Acknowledging the importance of OSE and taste exposure can help to understand why some strategies to decrease eating rate are more effective in reducing food intake than others. For example, smaller bite sizes strongly influence the relative taste exposure per gram consumed. Comparing large bites of 15 g with 3 × 5 g bites administered in cycles of 15 s, thus equal eating rate, increased OSE and reduced food intake by 22% (Bolhuis, Lakemond, et al., 2014). Mosca et al. (2019) showed that slow eaters took bites of 11 g whereas faster eaters had nearly double the bite size with 20 g, and an even shorter OSE per bite (12 vs. 15 s/bite in fast vs slow group, respectively). In this example, smaller bites doubled the taste exposure per gram of food for slower eaters, and their food intake was less than half that of the faster eaters (261 g v 550 g). A decreased bite size has previously been shown to produce significant reductions in ad libitum intake across several controlled human feeding studies (Bolhuis et al., 2011; Bolhuis et al., 2013; Bolhuis, Lakemond, et al., 2014; Weijzen et al., 2009; Zijlstra, De Wijk, Mars, Stafleu, & De Graaf, 2009). Moreover, using utensil that stimulate smaller bite sizes, such as chopsticks or forks instead of spoons also have shown to reduce eating rate and food intake (Bolhuis & Keast, 2016; Hogenkamp et al., 2010; Sun et al., 2015).

Decreasing the bite frequency within a meal is effective to slow down eating rate, but prolonging pauses between bites does not necessarily increase taste exposure, and has been shown to be less effective. Decreasing bite frequency failed to lower food intake across a number of experimental studies (Hermans et al., 2017; Lemmens, Martens, Born, Martens, & Westerterp-Plantenga, 2011; Yeomans, Gray, Mitchell, & True, 1997). Moreover, decreasing bite frequency requires an external cue or prompt beyond the food being consumed, which may distract the eaters attention, and disrupts their natural eating behaviour.

In addition to decreased bite size, increasing the chewing cycles per bite increases OSE and taste exposure. The number of chewing cycles and chewing duration is strongly co-linear with OSE, with correlations between 0.89 and 0.97 (Bolhuis, Forde, et al., 2014; Mosca et al., 2019), indicating that chews per bite determines the OSE time. Increasing chewing cycles has been shown to be effective at reducing food intake (Li et al., 2011; Mosca et al., 2019; Smit, Kemsley, Tapp, & Henry, 2011). The number of chew cycles rather than the frequency of chews (chews/s) has been shown to be important when reducing ER and intake. Chew frequency has been shown to be relatively consistent across different food textures, and is in itself not related to ad libitum intake (Forde et al., 2017; Ioakimidis et al., 2011), with approximately 0.9–1.2 chews per second (Aguayo-Mendoza et al., 2019; Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013a) and no difference between fast and slow eaters (de Lavergne, Derks, Ketel, de Wijk, & Stieger, 2015).

Taken together, reductions in eating rate often decrease food intake, and although the precise mechanism remains unclear, it seems likely that increased chews per bite and longer OSE are both likely to contribute to the earlier onset of satiation. Knowing that smaller bite size, increased chews per bite and the associated increased OSE time are key oral processing characteristics that can reduce food intake, creates opportunities to develop textural manipulations that encourage these behaviors during consumption. The next section consolidates the evidence on how each specific food texture parameter is known to moderate oral processing behaviors.

6. Using food texture to moderate oral processing

The food properties that have the strongest effect in moderating food oral processing are summarised in Table 2. For solids this most relates to properties associated with resistance of the food to breakdown during consumption, whereas for liquids this entails increasing viscosity and including particles. For solid food, manipulating food hardness, stiffness, chewiness and elasticity is likely to have the strongest effect on oral

Table 2
Overview of studies where texture manipulations show effects on eating behaviours and food intake. Directions of effects are shown with – or +. For example, increasing shear viscosity reduces drinkable bite size and eating rate.

Texture Modification	Impact on Eating Behaviours	Possible Applications	References
Semi-Solids			
Shear viscosity	Drinkable: bite size (−) Spoonable: bite size (+) ER (−), OSE (+) Expected satiation (+)	Enhanced satiety for yogurts, soups or other liquids and semi-solid foods	(Aguayo-Mendoza et al., 2019; De Wijk et al., 2008; Hogenkamp et al., 2012; Hogenkamp, Stafleu, Mars, Brunstrom, & de Graaf, 2011; Mars, Hogenkamp, Gosses, Stafleu, & De Graaf, 2009; McCrickerd et al., 2017; Tarrega, Marcano, & Fiszman, 2016; Zijlstra et al., 2008)
Extensional viscosity/Fluid cohesiveness	OSE (+)	Combination of thickeners and dispersion media in liquids/semi solid foods	(Chen & Lolivret, 2011; Hadde & Chen, 2019; Hadde et al., 2019)
Solids			
Hardness/Stiffness	Bite size (−) Chews (+) ER (−) Food intake (−) Expected satiation (+) Saliva incorporation (+)	All kinds of solid foods (bread, cheese, sweet and savory snacks, breakfast cereals) including particles in semi solids and solid foods heterogeneous foods.	(Aguayo-Mendoza et al., 2020; Aguayo-Mendoza et al., 2019; Bolhuis, Forde, et al., 2014; de Lavergne et al., 2015; Foster et al., 2006; Lasschuijt et al., 2017) Koc et al. (2014)
Elasticity/ Chewiness/ Springiness	Chews (+) OSE (+) ER (−)	Meat (replacers), protein containing foods, cheese. Particles in semi solids and solid foods heterogeneous foods.	(Cakir et al., 2012; Forde et al., 2017; Koc et al., 2014; Wee et al., 2018)
Toughness	Chews (+)	Fibrous foods, meats, meat replacers	(Mioche et al., 2003; Mioche, Bourdiol, Monier, & Martin, 2002)
Particle Number (and size)	Chews (+), ER (+)	Particles in semi solids like dairy products, soups, or solids like bars	(Aguayo-Mendoza et al., 2020; Mosca et al., 2019, p. 142)
Lubrication	Chews (−) ER (+) Bite size (+)	Solid foods for vulnerable populations (i.e., elderly, those who are underweight)	(Engelen et al., 2005; Gaviao et al., 2004; Motoi et al., 2013; van Eck, Wijne, et al., 2019; Wee et al., 2018)
Size of food pieces (relative to % w/w)	Chews (−) ER (−)	Sweet and savoury snack foods, fruits, vegetables, salads.	(Kohyama et al., 2005; Kohyama et al., 2007; Liem & Russell, 2019; van Eck, Wijne, et al., 2019; Weijzen et al., 2008)
Shape of particles/ pieces	Cubes: Chews (−) Thin long: Chew (+)	Snacks, particles in semi solids	van Eck, Wijne, et al. (2019)

processing behaviours and eating rates (Aguayo-Mendoza et al., 2019; Wee, Goh, Stieger, & Forde, 2018). When eating, we adapt our bite size for a given food according to the anticipated degree of oral processing and saliva required to form a cohesive bolus, with smaller bites for foods that are expected to require extensive mastication for particle breakdown and/or saliva incorporation (Bolhuis, Forde, et al., 2014; Forde et al., 2017; Lasschuijt et al., 2017). Foods that are dry and fracture into small pieces that require extensive moisture for agglomeration (e.g. tortilla chips) are taken in small bites and chewed for longer, whereas those foods that are already moist and deform easily (e.g. canned tomatoes) are taken in larger bites and chewed for a shorter time (Forde et al., 2017; Forde et al., 2013a; Wee et al., 2018). Geometrical properties including shape, size and number of pieces can also influence fracture properties and oral processing parameters such as bite size and chews per bite. The size and shape of foods influence the available surface area for moisture uptake, or added condiments such as toppings or sauces. Adding condiments to a carrier food can have the dual effect of increasing both the energy content and lubrication/eating rate of the ingested composite food.

6.1. Viscosity

The viscosity or 'thickness' of a fluid is measured as the fluid's resistance to flow (Vliet, 1999). Extensive research has been shown that higher viscosity leads to decreases in eating rate and ad libitum intake (Table 1). Highly viscous foods promote increased OSE and require more oral processing before swallowing (Aguayo-Mendoza et al., 2019; McCrickerd, Lim, Leong, Chia, & Forde, 2017; Zijlstra, Mars, De Wijk, Westerterp-Plantenga, & De Graaf, 2008). However, (Mosca et al., 2019) and van Eck et al. (2020) found no effect of viscosity on either eating rate or ad libitum intake, suggesting that the increases viscosity were too small to sufficiently impact oral processing or ad libitum intake. In addition to increased viscosity, the utensils used during consumption also played a role. Using straws in the study of Zijlstra et al. (2008) led to significant decreases in sip size and intake when viscosity of a yogurt drink was increased (De Wijk, Zijlstra, Mars, De Graaf, & Prinz, 2008). By contrast, in studies where the test food was consumed using a spoon, higher viscosity can often lead to increased bite size, as a more viscous food can adhere to the spoon more effectively (McCrickerd et al., 2017; Mosca et al., 2019). This means that increasing a fluids viscosity is more effective at reducing ad libitum intake for drinkable foods (i.e. milkshakes) due to the impact on sip size, whereas for spoonable foods an increase in viscosity is more likely to increase bite size thus might have a smaller effect on eating rate and ad libitum intake (De Wijk et al., 2008; Hogenkamp et al., 2010; McCrickerd et al., 2017).

A promising, though not well studied, parameter in relation to ad libitum intake behaviour is extensional viscosity or elongation viscosity, which refers to a foods stickiness. Chen and Lolivret (2011) have shown that both shear viscosity as well as extensional viscosity, measured as fluid stretching behaviour, were both positively related to OSE time, measured across 18 fluid foods (i.e. milk, juices, jam, honey, peanut butter). Modifications to extensional viscosity are achieved through the choice of thickening agent used in a given food matrix. Fluids thickened with xanthan gum have a much higher maximum extensional viscosity than fluids thickened with modified starch at a similar shear viscosity (Hadde & Chen, 2019; Hadde, Cichero, Zhao, Chen, & Chen, 2019). It is plausible that increasing the extensional viscosity or 'stickiness' of a food may decrease intake via increased OSE time and smaller bite sizes. Conversely, reductions in extensional viscosity are likely to reduce eating effort and could be used to increase food intake, for example when trying to stimulate intake within a vulnerable population.

6.2. Hardness, elasticity and plastic behaviours

Solid foods can be classified as soft-solids, that require chewing but do not have "crispy" attributes (e.g., cheese); or hard-solid foods that are crispy and have an associated acoustic emission (e.g., crackers). In terms of the trajectory of an oral break down path (explained in 4.0, Fig. 2), harder foods require more chewing cycles and a longer time to modify food texture and disrupt their innate structures and fibres (e.g. coconut, carrots). Harder foods need to be fractured into smaller particle sizes to facilitate sufficient particle softening and bolus lubrication for agglomeration before swallowing (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007). For example, consuming moist peanuts shows larger bolus particle size than consumption of dry peanut prior to swallow (Hutchings et al., 2011). Ad libitum intake studies have previously shown that increased hardness leads to smaller average bite size, longer OSE, increased chews per bite and a 9–21% reduction in ad libitum energy intake (Tables 1 and 2).

The bulk rheological properties of solid foods are described by the response of the food to mechanical deformation during mastication, and is summarised as either elastic or plastic behaviour (Vliet, 1999,). Elastic behaviour describes the relationship between the applied force, mechanical deformation and recovery of the food, and is associated with instrumental texture parameters such as 'springiness', 'chewiness' and 'resilience'. Highly elastic foods tend to recover much of their original form following deformation, and thus require extensive mastication to break down the original structure, examples are squid or beef (Wee et al., 2018). Elastic foods deform (strain) instantaneously when a weight (stress) is applied. The strain disappears instantaneously when the stress is removed and the product completely recovers to its original height and shape. By contrast, plastic foods are described by the yield stress needed to fracture the food into smaller pieces, where highly plastic foods fracture easily into smaller, harder particles with a greatly increased surface area. Unlike elastic foods, plastic foods do not return to their original shape when the stress is removed as they exhibit a yield stress which, when exceeded, causes flow and permanent deformation of the product. Highly plastic foods are crispy or crunchy and often described as gritty and cohesive, like potato chips or crunchy cookies (de Lavergne, van de Velde, & Stieger, 2017). Another study increased elasticity (jellied confectionary) and plasticity (caramel) and compared chewing behaviour (Foster, Woda, & Peyron, 2006). Four jelly foods differing in elasticity were measured by fracture strain and four caramel differing in plasticity were measured by fracture stress. The four food items could be distinguished on "hardness" by a sensory panel in both the elastic and plastic foods. Increasing either plasticity or elasticity led to longer chewing time, increased chew cycles and cycle duration. In agreement, others have shown that model foods varied in their hardness showed an increased number of chews and longer chewing duration (OSE) when both fracture stress or fracture strain were increased (Barrangou, Daubert, & Foegeding, 2006; Koc et al., 2014).

Food fracturability is inversely related to the toughness and stiffness such that foods that fracture easily tend to have a low toughness and stiffness, for example silken tofu (Agrawal, Lucas, Prinz, & Bruce, 1997). Foods that exhibit more elastic behaviours have a low fracturability and are highly resilient to mechanical deformation such that they require a greater number of chewing cycles to reduce bolus structure adequately to form a bolus for swallow (Wee et al., 2018). In general, plastic foods can often be consumed at a faster eating rate due to a high fracturability compared to elastic foods that need generally more chewing cycles to form a swallowable bolus (Foster et al., 2006; Koc et al., 2014) (Fig. 2). The same behaviours were observed when comparing hardness in real foods that show elastic behaviours, where higher elasticity was associated with increased 'springiness', 'chewiness', and 'resilience' and chews per bite in the intermediate and later phases of oral processing to reduce overall eating rate (Wee et al., 2018). During the oral processing of meat, the toughness and tenderness determined the chewing behaviour from initial until later stages of oral processing. Tough meat increased the chewing duration needed to fracture meat fibres, and increased the quantity of saliva incorporation needed prior to swallowing (Mioche, Bourdiol, & Monier, 2003) (Table 2). Increasing the elastic properties for certain foods, including 'springiness' or 'chewiness' can increase the chews per bite substantially in all phases of oral processing, and is a more effective approach to reducing eating rate and food intake than simply focussing on hardness alone.

6.3. Bolus lubrication, fracturability and condiments

Bolus food particles need to reduce in size, soften and become fully coated and lubricated to form a cohesive mass that can be swallowed safely (Fig. 1). Saliva secretion is stimulated by chewing and the moisture content of the bolus and saliva uptake increase linearly with longer chewing (Gaviao, Engelen, & van der Bilt, 2004; Motoi, Morgenstern, Hedderley, Wilson, & Balita, 2013). The initial degree of lubrication contributes significantly to the breakdown path for a given food, and can influence the length of time needed to sufficiently lubricate the bolus. Foods with lower innate lubrication require more saliva incorporation and a greater number of chewing cycles to lubricate sufficiently for bolus agglomeration and cohesion. Moisture content, dry matter percentage and fat content determine the degree of innate lubrication for a given food, and consequently how much saliva is required for bolus formation (Gaviao et al., 2004; Mosca & Chen, 2017). Foods with a higher moisture or fat content need less chewing to achieve sufficient lubrication for safe swallow (Gaviao et al., 2004; Motoi et al., 2013). Hard and dry foods need more chewing before swallowing, for example an average of 17 chew cycles for cake, compared to 63 chews for an equivalent weight of carrots (Engelen et al., 2005).

Importantly, the rate of saliva incorporation is influenced by the available surface area of the bolus and the absorption capacity of the food (Mosca & Chen, 2017). In this regard, foods that fracture easily into smaller pieces and have a large surface area, such as brittle foods like crisps, are likely to absorb saliva faster than foods that require more intensive deformation to achieve smaller particles (i.e. nuts). The absorption properties of the food play a role, as food materials that cannot readily absorb moisture or are coated in a hydrophobic coating, may also require longer to chew to lubricate before swallowing (Prinz & Lucas, 1997). Earlier we described how food 'hardness' can influence bite size and force. Food 'fracturability' is a measure of the tendency to fracture, crumble, crack or shatter in response to force, and is often associated with the sensory attributes 'crumbliness', 'crispiness', 'crunchiness' and 'brittleness'. The fracturability of a food is determined by its 'toughness', or capacity to absorb energy and plastically deform without fracturing, and its stiffness or rigidity. Fracturability influences eating rate by affecting the rate of increase in bolus particle surface area during mastication, and through this influencing the rate of lubrication (Fig. 2). Smaller bolus particles are harder to fracture, and bolus particle hardness (i.e. the energy required to fracture into smaller particles) and stiffness (i.e. Young's modulus) influence the rate and extent of particle size breakdown and available surface area for saliva uptake (Mosca & Chen, 2017; Prinz & Lucas, 1997). For example, a stiff food with low toughness, such as a thin potato chip, can fracture easily and will rapidly increase bolus surface area leading to increased saliva uptake and overall eating rate. However, manipulation of these parameters can impact the rate of breakdown and saliva uptake, and through this speed up or slow down the rate of lubrication and eating rate. To date, studies have not systematically manipulated bolus fracture and lubrication properties to observe their impact on eating rate or ad libitum intake.

Condiments such as butter, mayonnaise or sauces are frequently consumed with carrier foods like breads or crackers, and can greatly increase lubrication compared to consuming a carrier food on its own. Adding condiments to a carrier food can enhance palatability, and greatly increase the lubrication of the composite material, thus speeding up the eating rate (van Eck, Hardeman, et al., 2019). For example, when mayonnaise is added to carrots they are eaten faster, though the swallowed boli contain larger particles sizes than when the carrot is not consumed with a condiment (van Eck, Wijne, Fogliano, Stieger, & Scholten, 2019). This indicates that adding a condiment leads to decreased chews per bite, and lubricates bolus particles such that it reduces the need for further particle breakdown and saliva incorporation, to increase the eating rate (Hutchings et al., 2011). Moreover, adding mayonnaise, cheese spread, or butter to bread and crackers also increases eating rate and decreases chewing duration when compared to the consumption of plain bread and crackers (Engelen et al., 2005; van Eck, Hardeman, et al., 2019). Consuming bread and crackers with a firm cheese decreased saliva incorporation but did not decrease the total chewing duration, presumably due to the structure and lubricant properties of the firm cheese. Therefore, the textural and lubrication properties of both the carrier food and added condiment determine the effect on saliva incorporation, chewing duration and eating rate. Condiments that are high in fat (lubrication, cohesion) or low in viscosity (wetting/moistening) are the most effective at increasing bolus lubrication, producing the largest reductions in chews per bite, and largest increases in eating rate (van Eck, Fogliano, Galindo-Cuspinera, Scholten, & Stieger, 2019; van Eck, Wijne, et al., 2019).

Moreover, adding condiments significantly increase the overall energy density of the composite food. Adding a condiment such as butter or mayonnaise accelerates both the eating rate (g/min) as the rate of energy intake (EIR; kcals/min), which has previously been shown to encourage passive energy over-consumption (Hall et al., 2019).

6.4. Shape and size

Oral processing behaviours can also be influenced by a foods geometrical parameters including shape, size and number of food pieces in products such as biscuits or snacks, or number of particles in products such as soups, yoghurts or solids bars with inclusions (Table 2). The size and shape of food pieces can influence the bite size with which a product is consumed. Previous research has shown that consuming smaller pieces reduced eating rate and food intake compared to similar foods served in larger bars, due to the impact of bite size on eating rates (Weijzen, Liem, Zandstra, & de Graaf, 2008). In a recent study, ad libitum intake was greater for whole carrots compared to diced carrots (Liem & Russell, 2019), wherein the whole piece prompted larger average bite sizes that accelerated and increased intake. Previous work by Hutchings et al. (2009) has shown that average bite size is dependent on a foods length. Taken together, these findings suggest that individuals adjust their bite sizes in response to a foods shape and size to a maximal but comfortable length when consuming lengthy food (e.g., carrots, bars), whereas smaller pieces have relatively larger volumes which lead to less gram per bite, thus smaller bite sizes in grams but not in volume. These findings illustrate that is possible to moderate eating rate and oral processing behaviours of snack foods by specifying a product size/length and shape that prompts a predetermined bite size and encourages a desired consumption behaviour.

In addition to effects on bite size, shape and size also influence chewing behaviours during consumption. Conventional wisdom suggests that cutting foods finely may reduce chewing effort and the in-mouth duration required to swallow, and may be more suitable for vulnerable populations or those with chewing difficulties. However, when smaller pieces were compared to larger pieces or whole foods like apples with similar weight, smaller pieces tended to increase the number of chewing cycles and OSE duration, being consumed with a slower eating rate (Kohyama, Nakayama, Watanabe, & Sasaki, 2005; Kohyama et al., 2007; van Eck, Wijne, et al., 2019). A recent study compared chewing behaviour of carrots with the same total weight but different shapes (cubes vs long thin spiralized pieces vs. julienne) and different sizes (large vs small) (van Eck, Wijne, et al., 2019). For size, one large cube required the lowest number of chews and shortest chewing duration per gram compared to all of the different pre-cut carrot types whereas for shape, julienne carrots required the most chewing cycles when compared to cubes per gram consumed. Smaller particles are less likely than larger pieces to fracture during a chewing cycle. The larger surface area of long thin pieces required more chewing cycles and salivation before swallowing, as was seen with the julienne carrot samples.

However, foods with a high fracture stress and relatively low deformation (e.g. plastic behaviour) required increased chewing duration when consumed as smaller pieces, whereas foods that fracture at lower stress and large deformation (e.g., elastic behaviour, such as meats, surimi gels) similar chewing durations were found for different food sizes with equal weights (Kohyama et al., 2007).

Particle shape and size in liquid foods like soups or dairy products may also influence oral processing and ad libitum intake. Peach gel particles added to a yoghurt were shown to decrease its eating rate by up to 60%, where the hardness of the particles and the weight percentage of particles further increased the number of chews and slowed down the eating rate (Aguayo-Mendoza et al., 2020). Another study added granola particles of 6 mm or 12 mm to yogurts at a constant weight percentage, which resulted in a 2-fold increase in particle number for the smaller particle condition, this led to an 8% lower ad libitum intake of the yoghurt with smaller and more particles (Mosca et al., 2019). The smaller particle condition was associated with an increased number of chews and a 15% lower eating rate (Table 1). This effect was explained by the increased volume and surface area of the smaller particles and the increased total number of particles.

Food size and shape can also significantly influence the quantity of condiments and sauces that can be held by a carrier food where foods with larger surface area have a greater capacity to hold more of a condiment or sauce and can speed up consumption rates. Through this, the size or shape of a food carrier such as bread or pasta, can be used to manipulate the available surface area and increase or reduce the quantity of condiment or sauce consumed and the rate of energy intake (van Eck et al., 2020).

7. The future of reformulation; application of food texture and energy density to moderate intake

The current paper consolidates the research to date on the impact of food textural properties on oral processing, and highlight opportunities to moderate energy intake. By understanding a foods breakdown pathway, it is possible to target specific elements of structure and lubrication to directly influence a foods eating rate and the extent to which it is likely to be consumed. Fig. 3 summarizes how textural manipulations can combine to influence food structure, lubrication and oral processing behaviors that slow eating rate and reduce energy intake. Well studied food textures in relation to food intake are viscosity in semi solids foods, and hardness and elasticity in solid foods. Less research has been done regarding food size and shape and the use of condiments. Well established oral processing characteristics that reduce food intake are decreased bite size and enhanced chews per bite. Solid foods with harder and more elastic structures are likely to reduce the eating rate by decreasing bite sizes and more chews per bite which lead to lower food intake. Increasing viscosity in semi-solids like dairy products will also increase the OSE time and decrease food intake. Addition of particles, especially those with elastic characteristics (e.g., dried fruits) are expected to decrease the eating rate and could be beneficial to moderate energy intake and enhance satiety per kcal.

For semi-solid and liquid foods, increasing the shear viscosity have been shown to moderate energy intake, especially for drinkable foods due to natural decreases in sip sizes (Tables 1 and 2). Addition of low energy dense thickening ingredients such as Tara Gum, Xanthan gum or adjustments in stirring or cooling processes can increase viscosity without significant increases a products energy density. Increasing the extensional viscosity has potential to decrease eating rate and food intake, though future studies are required to test the efficacy of this approach. For certain product categories, the addition of particles will increase chewing duration and slow eating rate, with smaller particles and large surface area having the largest impact on chews per bite, eating rate and intake. For solid foods, increased hardness leads to more chewing cycles, smaller bite sizes, reduced eating rate and energy intake. Where possible, moving foods away from plastic to more elastic behaviors such as increased 'chewiness', 'springiness' and 'resilience' leads to longer chewing over all oral processing phases from initial bite until swallowing (Fig. 2).

A foods size and shape have been shown to influence oral processing and food intake, where sizes/shapes that encourage smaller bites and increased chews per bite will slow the eating rate and support lower intakes. Particles in soups, salads or dairy products that have a larger surface area, such as thin long pieces rather than large cubes, have also been shown to slow the eating rate. Finally, for composite foods, the size and shape of the carrier food can influence the available surface area and the capacity of the carrier to hold condiments or sauces. For example, by adjusting the size and shape of French fries, the surface to hold energy dense sauces can be influenced. This in turn can influence in –mouth lubrication, energy intake rate (kcals/min) and energy consumption.

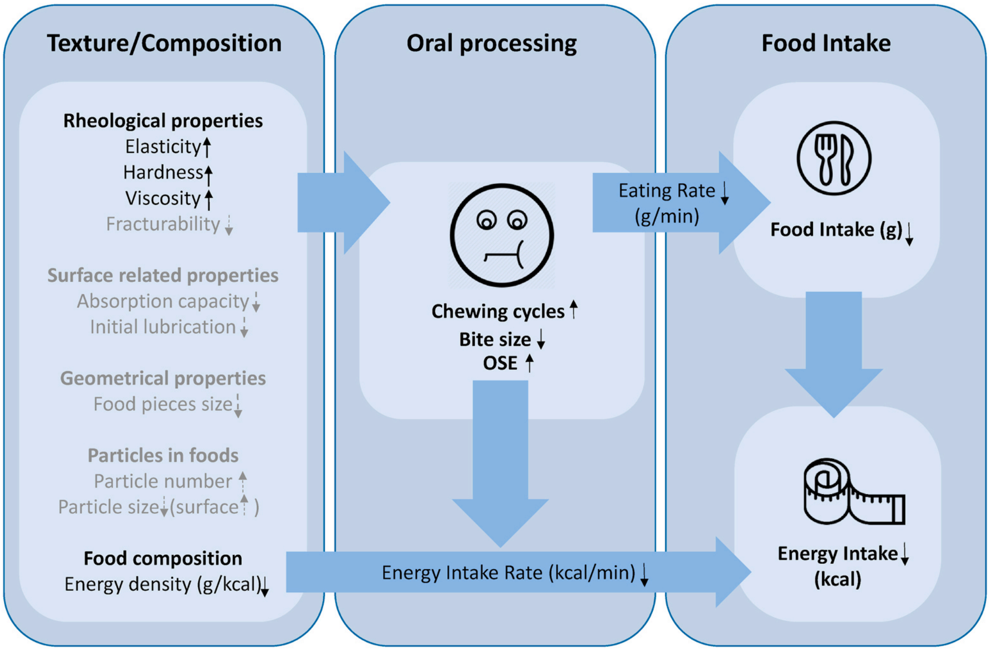

Fig. 3. Visualization of how food textural properties moderate eating rate and energy intake via oral processing. Black arrows indicate well studied directions, grey arrows indicate that more research is needed to confirm these directions. The arrows in the textural parameters are in the direction to moderate oral processing and decreasing energy intake. For example, harder foods with low absorption capacity need more time for lubrication which is associated with increased chewing and OSE which leads to smaller bite sizes, all these oral processing characteristics will decrease eating rate and ultimately energy intake.

A potential concern for the aforementioned texture modifications could be that foods designed in this way may develop undesirable sensory properties and become too hard or dry to meet consumer appeal. In this respect it may be advisable to make smaller changes along several textural properties to decrease eating rate while maintaining palatability and product acceptance. Previous research has shown that it is also possible to manipulate the texture properties and maintain (Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013b) or enhance their hedonic appeal (McCrickerd et al., 2017). Modifying the size and shape of food pieces is unlikely to have a profound effect on food liking, but may offer new approaches to designing the consumption experience, with particular relevance for snack food intake.

For vulnerable populations such as older consumers or those with reduced oral processing capacity, understanding the texture challenges that moderate oral breakdown and designing foods to overcome this, can lead to the development of new structures to promote more comfortable eating and increased food intake. For this population, increasing innate lubrication, for example by increasing the fat content, and designing the fracture properties to enhance softening and agglomeration could be used to stimulate eating rate and intake. Recent advances in our understanding of how condiments interact with the structural and surface properties of carrier foods may be used to both increase the rate of consumption, and energy content per bite. Similarly, when trying to stimulate vegetable and fruit intake among children, evidence suggests these should not be finely cut, but offered in larger pieces to stimulate larger bite size and faster intake (Kohyama et al., 2005; Liem & Russell, 2019; van Eck, Wijne, et al., 2019).

Although texture manipulations have been shown to decrease energy intake without loss in post meal satiety or energy compensation in next meals, longer term trials are needed to confirm sustained impact of reductions to eating rate and energy intake, and possible links to body weight. Today we still do not know, what are the limits of texture-based oral processing manipulations? Can acute differences in eating rate be sustained in the longer-term, or do we learn to adjust our oral processing behaviors to new texture challenges over-time? How malleable is your preferred eating rate for your favorite foods or product categories? These questions remain unanswered, and should inform future research in this area. Future research requires controlled human feeding interventions that go beyond acute feeding trials, to explore the longer-term impact of individual and combinations of texture properties to evaluate the impact on intake.

Whereas the impact of individual texture parameters on oral processing has been studied, often this has been in a model or single food system, whereas our dietary behaviour comprise many different foods that are typically consumed in combination. Recent research on composite foods has demonstrated the complexity of how food structures combine and interact to influence oral processing behaviors during consumption. Predicting oral processing behaviors for model foods with linear changes in a single texture dimension (i.e. hardness), is a poor reflection of the oral processing experienced when consuming heterogeneous foods that consist of multiple interacting texture variables. The current paper has highlighted some universal texture manipulations that can slow eating rate, yet within a given category less is known about the hierarchy of effect sizes when comparing the influence of different texture or lubrication manipulations. Is the energy intake rate of a meal dictated by the eating rate of its slowest component? Can food structure modifications be over-ruled by increasing in-mouth lubrication? For example, in one previous feeding trial, harder burger buns determined the energy intake rate of the whole meal, and supported reductions in overall energy consumed (Bolhuis, Forde, et al., 2014). Similarly, there were a similar number of chews and chewing duration for plain bread compared to bread with a firm cheese, despite a larger food mass and significantly higher energy density in the bread and cheese combination (van Eck, Hardeman, et al., 2019). In many composite food combinations, the carrier food is typically the hardest/toughest food, and has a dominant effect on the rate of consumption (van Eck, Wijne, et al., 2019). A future challenge in the application of structures to moderate oral processing and energy intakes, will be the need to strike a balance between achieving food textures that can successfully moderate eating rate, while maintaining consumer acceptance and sensory appeal.

8. Conclusions

This review consolidates the available evidence on the role of food structure in moderating oral processing behaviour, and through this reduce eating rate and energy intake across a wide range of different food categories. Many of the modern processed foods that are associated with greater energy intakes are softly textured and energy dense, which together creates a higher rate of energy intake that is likely to promote passive overconsumption (Forde et al., 2020). Whereas the impact of reducing energy density is well known (Rolls, 2009), the importance of texture based reductions to eating rate have until recently been less well understood. A deeper understanding of how food structures affect bite size and the number of chewing chewing cycles needed to prepare a bolus for swallow will help guide the development of food structure ‘design principles’, that can be used to go beyond sensory appeal to guide and direct the eating experience and potentially moderate energy intake over time. In this respect, applying food structure modifications to direct consumption behaviour creates new opportunities to go beyond traditional compositional reformulation approaches that solely focus on reducing salt, sugar, fat or portion size. Future research should address the gaps in our current understanding, and create new opportunities to apply texture based interventions to improve control over habitual energy intake behaviours.

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