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Oral processing behavior, sensory perception and intake of composite foods

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A R T I C L E I N F O

Keywords:
Maximum of 6 composite foods
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A B S T R A C T

Background: Consumers frequently combine foods with different compositions and properties within a meal or within a bite; for example bread with spreads or vegetables with dressings. Such food combinations are called composite foods.

Scope and approach: This narrative review highlights how (1) addition of food particles and (2) addition of accompanying foods influence oral processing behavior, sensory perception and intake of composite foods. Practical implications, knowledge gaps and future perspectives are also discussed.

Key findings: Oral processing behavior of composite foods can be modified by changing single food properties. Adding particles, adding accompanying foods or changing single food properties, especially mechanical properties, shape and concentration, are promising approaches to influence eating rate and thereby energy intake. In addition, sensory perception of composite foods is complex, as interactions between foods in mouth imply significant changes in sensory perception. Consequently, sensitivity to discriminate between foods is reduced when a food is assessed together with an accompanying food.

Conclusions: This review highlights how structural transitions of composite foods during mastication contribute to oral processing behavior, perception and intake of composite foods. This is of particular interest in the design of healthy or sustainable produced foods, for which assuring excellent sensory quality still poses a challenge.

1. Introduction

Foods are consumed to obtain energy and nutrients for the human body and to experience pleasure and reward. Although consumers pursue values such as health, perceived sensory characteristics are an important driver of food appreciation and pleasure during the course of eating. In daily life, this often presents a paradox: the healthier, nutritious food options are frequently less liked by consumers whereas highly palatable and often energy-dense foods are easily overconsumed, contributing to diet-related non-communicable diseases. Understanding which factors contribute to food intake (i.e. when, what, how much do consumers eat) and sensory perception (i.e. why do consumers eat/like what they eat) are of utmost importance for public health.

Food structure is known to modulate food oral processing behavior, by which both food intake (recommended reviews and meta analyses in this area: Campbell, Wagoner, & Foegeding, 2017; Krop et al., 2018; Robinson et al., 2014; Stribiţcaia, Evans, Gibbons, Blundell, & Sarkar, 2020) and sensory perception (recommended reviews in this area: Devezeaux Devezeaux de Lavergne, van deVelde, & Stieger, 2017; Foegeding, Vinyard, Essick, Guest, & Campbell, 2015) are affected. Fig. 1 highlights the role of food structure in relation to food oral processing, food intake and sensory perception.

In everyday life, consumers frequently combine foods with different compositions and properties within a meal or within a bite. For example, bread is often combined with spread and/or cheese, yogurt with fruits and/or granola or various vegetables combined with dressing into a salad. Throughout this review, the term composite foods refers to foods that are composed of two single foods, i.e. one solid carrier food (e.g. bread, vegetable) combined with one condiment (e.g. mayonnaise, cheese spread or dip). However, little is known about the relationships between food structure, oral processing behavior, sensory perception and intake of composite foods, although this is the most common consumption context. Recently, Scholten (2017) reviewed how microscopic inhomogeneity (from micron to mm size) in dispersions, emulsions and emulsion-filled gels affects sensory perception (Scholten, 2017). In addition, Galmarini (2020) reviewed theories, concepts and tasting methodologies related to food-beverage and food-food pairings Galmarini (2020). However, a systematic understanding of how different single foods varying in food properties (i.e. macroscopic inhomogeneity; from mm size and larger) contribute to oral processing behavior and

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consequently to sensory perception and intake of composite foods is still lacking.

In this review, an overview is provided on oral processing behavior and sensory perception of composite foods, displaying heterogeneity on a macroscopic length scale (mm size and larger). Foods to which particles varying in properties are added (e.g. soup with vegetable pieces, yogurt with fruit pieces, cheese with herbs or chocolate with nuts) and composite foods that are composed of two or more single foods varying in properties (e.g. bread/cracker with spreads or vegetables, meat, fish or staple foods with dressings or sauces) are discussed. This review provides new insights into the mechanisms underlying food oral processing of composite foods, and enables a better understanding of the structural transitions of composite foods that contribute to intake and perception. Section 2 gives an overview of oral processing behavior of heterogeneous foods. Section 3 provides an overview of sensory perception and consumer acceptance of heterogeneous foods. Section 4 gives an overview of eating rate and food intake of heterogeneous foods. Knowledge gaps and future perspectives are discussed in section 5.

2. Food oral processing behavior of heterogeneous foods

Tables 1A and 1B provide overviews of studies exploring food oral processing behavior of homogeneous foods to which macroscopic particles (typically mm size and larger) varying in properties were added (Table 1A) and of composite foods that were composed of two single foods varying in properties (Table 1B).

Addition of particles to homogeneous foods can be used to alter appearance, sensory perception and nutritional composition, but it also influences oral processing behavior and eating rate. More specifically, addition of particles to model foods (i.e. gels) and real foods (i.e. yogurt or cream cheese) increased oral processing time and number of chews until swallowing (Aguayo-Mendoza et al., 2020; Aguayo-Mendoza, Chatonidi; Piqueras-Fiszman, & Stieger; *submitted;* Krop, Hetherington, Miquel, & Sarkar, 2020; Laguna, Hetherington, Chen, Artigas, & Sarkar, 2016; Laguna & Sarkar, 2016; Morell; Tarrega; Foegeding, & Fiszman, 2018). Consequently, eating rate (g/min) decreased by the addition of solid particles to liquid or semi-solid matrices (i.e. 60% when peach gel particles were added to yogurt and 9–15% when bell pepper particles were added to cheese). The addition of solid particles to liquid or semi-solid matrices usually introduces the need to chew the composite foods to break down the structure of the particles and consequently oral processing time is prolonged.

To better understand how single foods contribute to oral processing behavior of composite foods, food oral processing behavior of bi-layer model gels with contrasting mechanical properties was studied (Devezeaux de Lavergne et al., 2016). Both layers contributed to oral processing behavior of the composite food gels, but hard gel layers were found to influence oral processing behavior slightly more than soft gel layers. Likewise, several studies have been performed on commercially available composite foods (Table 1B). Addition of butter to dry carriers such as toast and cake reduced oral processing time and the number of chews until swallowing (Engelen, Fontijn-Tekamp, & Van Der Bilt, 2005; Gavião, Engelen, & Van Der Bilt, 2004). Similarly, addition of cheese spread and mayonnaise reduced oral processing time and number of chews until swallowing for both dry bread and crackers (van Eck et al., 2019). Such liquid and semi-solid toppings moistened and softened the dry food bolus, and consequently less time and effort had to be spent on reducing structure and increasing lubrication before safe swallowing (van Eck et al., 2019; van Eck et al., 2020). Consequently, eating rate of bread increased by 104 and 136% and eating rate of crackers increased by 113 and 153% with the addition of semi-solid cheese spread and liquid/soft semi-solid mayonnaise, respectively (van Eck et al., 2019). Liquid or semi-solid condiments typically increase the lubricity of the composite food in comparison to the carrier food. Consumers masticate the foods until the food boli are sufficiently lubricated to be safely swallowed. This swallowing threshold is reached after a shorter oral processing time when carrier-condiment combinations are consumed compared to the carrier food alone.

When looking at distinctly different carriers such as vegetables (i.e. high moisture content, assumed to absorb little moisture), similar trends were found. Addition of mayonnaise reduced oral processing time and number of chews until swallowing for both raw carrot and potato (van Eck et al., 2020; Van Eck, Wijne; Fogliano; Stieger, & Scholten, 2019). Consequently, eating rate increased by 57% for raw carrot and by 77% for cooked potato upon addition of mayonnaise. Instead of acting as a food moistener and softener, the semi-solid and liquid condiments assisted in bolus formation of vegetables by adhering bolus pieces together to form a cohesive, safe-to-swallow bolus (van Eck et al., 2020). Thus, semi-solid and liquid toppings/condiments assisted saliva in bolus formation in two very different solid food categories (dry foods; foods with higher moisture content), but different facilitation mechanisms apply.

In everyday life, consumers frequently combine foods with different compositions and properties. Few studies investigated the influence of matrix properties (Table 1A), macroscopic particle properties (Table 1A) or single food properties (Table 1B) on oral processing behavior of

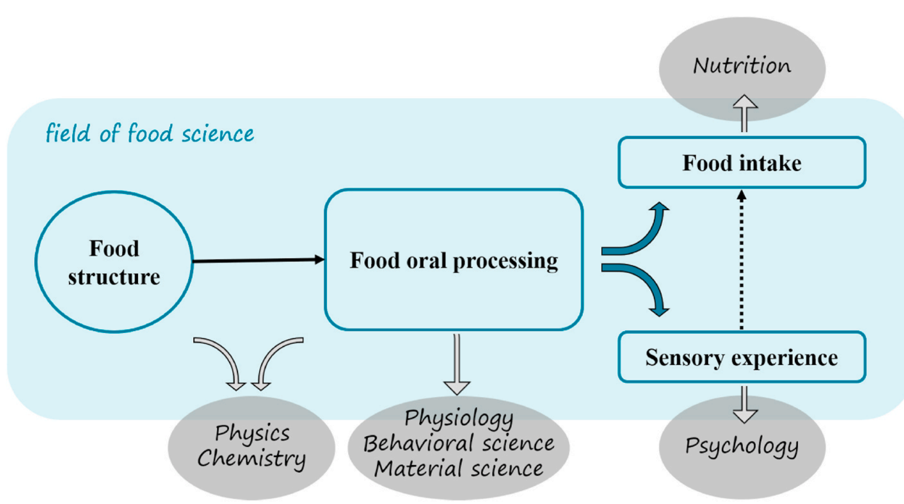

Fig. 1. A multi-disciplinary approach highlighting the role of food oral processing in relation to food structure, food intake and sensory perception. The different aspects of food science (in green) relate to other disciplines including physics, chemistry, physiology, behavioral science, material science, psychology and nutrition (in gray). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Summary of food oral processing behavior for (A) homogeneous foods to which particles varying in properties are added and for (B) composite foods that are composed of two single foods varying in properties.

1A: Food oral processing behavior of food with added particles

	Matrix (*varying in properties*)		Particles (*varying in properties*)		Method	Subjects	Main outcomes	Reference
model foods	carrageenan gel	–	calcium alginate	*inhomogeneity*	Oral processing behavior (video)	11 consumers	• Addition of gel particles to a gel matrix increased oral processing time and number of chews. • Oral processing time and number of chews increased with increasing matrix inhomogeneity.	Laguna and Sarkar (2016)
	carrageenan gel		calcium alginate	*size*	Oral processing behavior (video)	30 elderly consumers	• Oral processing time increased with the presence of textural heterogeneity compared to gel samples with one texture	Laguna et al. (2016)
	gelatin-agar gel	–	various gels	*textural complexity*	Oral processing behavior (recorded by researcher) Bolus properties	20 consumers	• Oral processing behavior was not influenced by variation in textural complexity. • Surrounding matrices controlled breakdown of embedded particles in terms of particle size.	Larsen, Tang, Ferguson, Morgenstern, and James (2016)
	gelatin gel chocolate	–	peanuts	*moisture content*	Oral processing behavior (recorded by researcher) Bolus properties	8 consumers	• Type of matrix influenced oral processing behavior and peanut particle breakdown (selection function). • Peanut particles did not influence oral processing behavior, but influenced the extent of particle breakdown (particle size, breakage function).	Hutchings et al. (2011)
commercial foods	yogurt	–	whey protein (microgel) apple cubes	-	Oral processing behavior (EMG, jaw tracking)	12 consumers	• Addition of microgel particles did not affect oral processing behavior. • Addition of apple cubes almost doubled the oral processing time, number of chews and muscle activity.	Morell et al. (2018)
	yogurt	–	peach gel	*size* *hardness* *concentration*	Oral processing behavior (video)	62 young consumers 62 elderly consumers	• Addition of particles increased oral processing time and number of chews, and decreased eating rate up to 60%. • Increasing particle hardness or particle concentration increased oral processing time and number of chews. • Particle size did not affect oral processing behavior.	Aguayo-Mendoza et al. (2020)
	cream cheese	*hardness*	bell pepper gel	*hardness* *concentration*	Oral processing behavior (video) Bolus properties	34 consumers	• Addition of particles increased oral processing time and number of chews, and decreased eating rate. • Cheese hardness affected oral processing behavior, as particle addition had a larger effect in soft cheeses than hard cheeses. • Increasing particle hardness increased the number of chews and decreased eating rate. • Particle concentration did not influence oral processing behavior.	(Aguayo-Mendoza et al., *submitted*)

1B: Food oral processing behavior of composite foods

	Food 1 (*varying in properties*)		Food 2 (*varying in properties*)		Method	Subjects	Main outcomes	Reference
model foods	gel layer 1	-	gel layer 2	-	Oral processing behavior (EMG) Bolus properties	10 consumers	• Oral processing behavior depended on both layers present. • Layers with high fracture stress layers slightly dominated oral processing behavior.	Devezeaux de Lavergne et al. (2016)

(*continued on next page*)

Table 1 (*continued*)

1B: Food oral processing behavior of composite foods

	Food 1 (*varying in properties*)		Food 2 (*varying in properties*)		Method	Subjects	Main outcomes	Reference
commercial foods	chocolate dessert layer	-	chocolate dessert layer	-	Combining behavior (video) Oral processing behavior (video)	32 consumers	• Most spoonfuls were composed of different layers.	Palczak et al., 2019
	melba toast		margarine		Oral processing behavior (jaw motion)	16 consumers	• Oral processing time and the number of chews until swallowing decreased when butter was added to toast.	Gavião et al. (2004)
	bread toast melba toast breakfast cake		butter		Oral processing behavior (jaw motion)	87 consumers	• Addition of butter reduced the number of chews until swallowing. • This effect was more pronounced in the dryer products.	Engelen et al. (2005)
	bread cracker		firm cheese cheese spread mayonnaise		Oral processing behavior (video) Bolus properties	18 consumers	• Addition of condiments decreased oral processing time and number of chews, and increased eating rate. • Condiments assisted bolus formation of bread/crackers by decreasing bolus firmness.	(van Eck et al., 2019)
	bread potato		mayonnaise	*fat content* *viscosity*	Oral processing behavior (EMG, jaw tracking) Bolus properties	16 consumers	• Addition of condiments decreased oral processing time and number of chews, and increased eating rate. • Decreasing the viscosity of mayonnaises fastened bolus formation. Fat content of mayonnaise did not influence oral processing behavior. • Condiments decreased bread firmness, increased potato cohesiveness and increased lubrication of both bread and potato bolus.	van Eck et al., 2020
	carrot	*shape*	mayonnaise	*fat content* *viscosity*	Oral processing behavior (video) Bolus properties	20 consumers	• Addition of condiments decreased oral processing time and number of chews, and increased eating rate. • Condiments assisted bolus formation of carrots by adhering carrot bolus particles into a cohesive bolus.	(van Eck et al., 2019)
	cracker	*shape*	cheese dip	*viscosity*	Oral processing behavior (video) Dipping behavior (hidden balances) *Ad libitum* intake	44 consumers	• Cracker shape influenced eating rate and *ad libitum* intake of cheese, as a larger amount of cheese was scooped with flat squared than finger-shape crackers • Small differences in cheese dip viscosity did not influence food oral processing behavior or *ad libitum* intake.	van Eck et al., 2020
	yogurt	*viscosity*	granola	*size*	Oral processing behavior (video) *Ad libitum* intake	104 consumers	• Yogurt viscosity did not influence eating rate and *ad libitum* intake, likely due to a change in spoon size. • Decreasing granola size decreased eating rate and *ad libitum* intake of yogurt with granola.	Mosca et al. (2019)

composite foods. Results indicate that oral processing behavior of composite foods can be modified by changing properties of components present. For foods with particles, increasing particle hardness decreased eating rate of yogurt by 30% (Aguayo-Mendoza et al., 2020) and eating rate of cheese by 5% (Aguayo-Mendoza, Chatonidi, Piqueras-Fiszman, & Stieger, *submitted)*. The impact of particle concentration depended on the matrix, as increased particle concentration increased oral processing time of yogurt (semi-solid) (Aguayo-Mendoza et al., 2020) but not of cheese (soft solid) (Aguayo-Mendoza et al., *submitted)*. For composite foods, changing food hardness (from bread to cracker) reduced eating rate of composite foods by 29–33%(van Eck et al., 2019). Similarly, eating rate was 32% lower for a lunch of hard foods than soft foods (i.e. hamburgers, rice salads) (Bolhuis et al., 2014). Changing solid food dimensions (e.g. shape, size) also affected oral processing behavior of composite foods. For instance, cutting carrots julienne (long, thin pieces) instead of cubes reduced eating rate of carrots by 17% (van Eck et al., 2019). A decrease in size of granola particles added to yogurt at constant weight concentration decreased eating rate by 7% and *ad libitum* intake by 5%. The volume or number of granola particles added to yogurt rather than the size of particles per se was suggested to be the driver of changes in oral processing behavior (Mosca et al., 2019). In both cases, the higher number of pre-cut, smaller pieces required more time to form a cohesive, safe-to-swallow bolus. Serving crackers varying in shape impacted eating rate of crackers with cheese by 17%, as an increase in cracker surface area facilitated higher cheese intake (van Eck et al., 2020). Regarding condiment properties, changing mayonnaise fat content or viscosity impacted eating rate of bread or cooked potato by 2–4% (van Eck et al., 2020). Hence, the current literature indicates that oral processing behavior of composite foods is mainly affected by the presence of particles or accompanying foods and, to a smaller extent, the specific properties of the food components.

3. Sensory perception and consumer acceptance of heterogeneous foods

Sensory perception of composite foods is known to be different from that of single foods. From the start of consumption, consumers are exposed to the different structures and flavors present in composite foods (Paulsen, Ueland; Nilsen; Öström, & Hersleth, 2012; Santagiuliana; Christaki; Piqueras-Fiszman; Scholten, & Stieger, 2018; Santagiuliana; Piqueras-Fiszman, van der Linden, Stieger, & Scholten, 2018; Tang, Larsen, Ferguson, & James, 2017). Upon mastication, the different foods are mixed in the mouth, leading to continuous transitions of the food structures present. This results in intra-oral sensory variety perceived throughout consumption, which has been suggested to be highly liked by consumers (Hyde & Witherly, 1993; Miele, Di Monaco, Cavella, & Masi, 2010; Szczesniak & Kahn, 1984).

Addition of food particles to homogeneous foods is usually perceived by consumers and sensory panels (Table 2A) so that gritty, grainy, beady, lumpy, chewy and rough sensations increase (Marcano, Morales, Vélez-Ruiz, & Fiszman, 2015; Morell, Tarrega, Foegeding, & Fiszman, 2018; Santagiuliana, Christaki, Piqueras-Fiszman, Scholten, & Stieger, 2018) and creaminess and smoothness sensations decrease (Krop, Hetherington, Holmes, Miquel, & Sarkar, 2019; Santagiuliana, Bhaskaran, Scholten, Piqueras-Fiszman, & Stieger, 2019; Shewan, Stokes, & Smyth, 2020). Stribiţcaia, Krop, Lewis, Holmes, & Sarkar (2020) showed that consumers were able to distinguish between homogeneous gels and gels with particles based on textural attributes such as hard, chewy and pasty, whereas they were not able to distinguish between gels with small and large-sized particles. The low modulus of the particles might have prevented detection of sensory differences based on particle size. This highlights that the mechanical properties of the embedded particles in relation to the matrix are of great importance for sensory perception of heterogenous foods (Krop, Hetherington, Holmes, et al., 2019). Santagiuliana et al. (2020) found that addition of micro particles (cellulose beads) to yogurt resulted in grittiness perception and decreased liking. Interestingly, they also showed that addition of well-liked large food particles such as peach or granola pieces to yogurt with gritty particles increased liking while grittiness was still perceived Santagiuliana et al. (2020). They suggested that the addition of large particles such as peach or granola pieces might have shifted consumer attention away from undesired sensations such as grittiness towards desired sensations.

For composite foods, consumer attention may shift from one food to another within one bite and back, and Temporal Dominance of Sensations was used to reveal which foods dominate sensory perception at which stages of consumption. Dynamic texture perception of bread-mayonnaise and carrot-mayonnaise combinations was dominated by the solid carrier foods, in particular at the beginning and end of a bite (van Eck, Fogliano, Galindo-Cuspinera, Scholten, & Stieger, 2019). Similar trends were found for yogurt with granola pieces, in which sensory perception was mainly dominated by the texture of granola such as crunchy and sticky (van Bommel; Stieger; Boelee; Schlich, & Jager, 2019). Solid foods require substantial oral breakdown before they can be swallowed safely, which leads to continuous changes in food structure thereby driving dynamic sensory perception of composite foods.

Sensory perception is changed when single foods are combined into composite foods (Table 2B), and flavor intensity perception generally decreased with the addition of an accompanying food (Cherdchu & Chambers, 2014; Meinert, Frøst, Bejerholm, & Aaslyng, 2011; Nguyen & Wismer, 2020; Paulsen, Ueland, Nilsen, Öström, & Hersleth, 2012; van Eck et al., 2019; van Eck et al., *submitted*). Consequently, consumers' sensitivity to discriminate between single foods varying in properties decreased (Nguyen & Wismer, 2020; van Eck et al., 2019). Several studies indicated that aroma compounds might be retained by the accompanying food matrix (Meinert et al., 2011; Traynor; Moreo, Cain, Burke, & Barry-Ryan, 2020). A recent study assessing *in vivo* aroma release indicates that such decreased sensory intensity perception is not simply a physicochemical effect, as aroma perception decreased while in-nose aroma release increased with the addition of accompanying foods (van Eck et al., *submitted*). Such incongruent data indicates that cognitive effects (i.e. distraction from one food by the presence of another food; sensory masking) might contribute to flavor perception of composite foods.

3.1. Practical implications: strategies to influence sensory perception and hedonic appreciation of foods

Sensory characteristics of foods are important determinants for consumer acceptance: if food does not taste good, it is not accepted and not eaten. Foods are rarely consumed alone, and interactions with accompanying foods and saliva provoke significant changes in sensory perception (Table 2). In everyday life, consumers combine certain foods to influence sensory perception. For example, condiments are added as a strategy to increase intake of vegetables or other unfamiliar foods among children (Cichero, 2017; Pliner & Stallberg-White, 2000). Both texture perception and flavor perception are changed when single foods are combined into composite foods. In general, perceived sensory intensity of a food decreases when an accompanying food is added (Cherdchu & Chambers, 2014; Meinert et al., 2011; Nguyen & Wismer, 2020; Paulsen et al., 2012; van Eck et al., 2019; van Eck et al., *submitted*). Both physicochemical and cognitive mechanisms have been suggested to explain this effect. From a physicochemical view, foods might interact in mouth and thereby reduce flavor release, leading to suppressed perception. Also a dilution effect might occur, as the concentration of flavor compounds from a single food is reduced by the addition of another food, thereby decreasing the intensity of its characteristic flavors (Kroll & Pilgrim, 1961). From a cognitive view, the presence of accompanying foods might distract consumers' attention away from the product of interest, leading to suppressed perception. In this context, van Eck et al., (*submitted)* show that cognitive effects play a key role in sensory perception of composite foods since the presence of an accompanying food increased the delivery of aroma compounds into the nasal cavity, but did result in lower perceived sensory intensity. Thus, single foods' flavor perception becomes less intense in the presence of accompanying foods, which can be desired in case of less-liked foods. However, the question whether the addition of accompanying foods and such a decrease in flavor perception impacts consumers' liking and consumers' actual eating behavior remains to be answered.

For composite foods, consumer attention may shift from one food to another within one bite and back, and Temporal Dominance of Sensations methodology was used to reveal which foods dominate sensory perception at which stages of consumption. Dynamic texture perception of composite foods was dominated by solid foods, in particular at the beginning and end of a bite. Solid foods require substantial oral breakdown before they can be swallowed safely, which leads to continuous changes in food structure thereby driving dynamic texture perception of composite foods. For composite foods, we speculate that the food requiring the highest degree of structural breakdown drives texture perception (when present above a certain ratio). Speculation about dynamic flavor perception in composite foods is more challenging, as flavor intensities differ substantially within food categories (e.g. vegetable bouillon vs. curry soup or watermelon vs. durian fruit).

3.2. Practical implications: should single foods or heterogeneous foods be assessed during new product development?

Assessing sensory perception of foods is important in product design. Sensory evaluations are generally performed with single foods, also when it concerns foods that are rarely consumed alone. For example, in case of mayonnaise, a spoon of mayonnaise rather than a mayonnaise-food combination is usually assessed during sensory evaluations. This raises the question how the sensory properties of foods that are rarely consumed on its own such as condiments including dressings, sauces, spreads etc. should be assessed. This review demonstrates that sensory characteristics of single foods are influenced by the presence of accompanying foods. A range of condiments was perceived to be different when consumed by themselves, but these differences were not perceived when combined with a carrier food (van Eck et al., 2019). Thus, sensory analyses of the single food itself tell only part of the story and might even be misleading product development. Although assessing

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Table 2

Summary of sensory perception for (A) homogeneous foods to which particles varying in properties are added and for (B) composite foods that are composed of two single foods varying in properties. Different sensory methods have been used, including Quantitative Descriptive Analysis (QDA), Descriptive Analysis (DA), Temporal Dominance of Sensations (TDS), Rate-All-That-Apply (RATA), Flash Profiling (FP), Sequential Profiling (SP) and Progressive Profiling (PP).

2A: Sensory perception of food with added particles

	Matrix (*varying in properties*)		Particles (*varying in properties*)		Method	Subjects	Main outcomes	Reference
model foods	carrageenan gel	-	calcium alginate	*inhomogeneity*	QDA	trained panel	• Addition of particles to gels increased perception of particle presence and particle size.	Laguna and Sarkar (2016)
	carrageenan gel		calcium alginate	*size*	Triangle DA	113 consumers 60 consumers	• Consumers were able to distinguish between homogeneous gels and gels with particles. • Consumers were not able to distinguish between small and large-sized particle gels.	Stribiţcaia, Krop, Lewin, Holmes, and Sarkar (2020)
	carrageenan gel		calcium alginate	*size*	QDA	semi-trained panel	• Addition of particles increased inhomogeneity perception and decreased smoothness perception.	Krop et al. (2020)
	gelatin-agar gel	-	various gels	*textural complexity*	DA TDS	20 consumers 21 consumers	• Increasing textural complexity generated a greater number of sensory descriptors during descriptive sensory analysis, and resulted in more frequent changes in texture attributes and in the selection of more unique texture attributes during TDS.	Tang et al. (2017)
	water novagel	-	agar (microgel)	*modulus* *concentration*	DA	trained panel	• Increasing particle modulus increased particle perception and decreased smoothness perception. • Particle detection was not influenced by particle concentration (50 vs. 80 w/w%).	Shewan et al. (2020)
	model soup model dairy food	-	K-carrageenan	*size* *hardness*	RATA	54 consumers	• The addition of small and hard particles led to gritty sensations, and the addition of larger particles triggered chewy, lumpy and beady sensations.	Santagiuliana, Christaki, et al. (2018)
commercial foods	yogurt	-	whey protein (microgel) apple cubes	-	FP	trained panel	• Addition of particles contributed to roughness, graininess and grittiness perception.	Morell et al. (2018)
	yogurt	-	peach gel	*size* *hardness* *concentration*	DA	62 young consumers 62 elderly consumers	• Increasing particle hardness or concentration increased hardness and chewiness perception. • Increasing particle size decreased creaminess and thickness perception.	Aguayo-Mendoza et al. (2020)
	yogurt	-	peach gel granola	*hardness*	Ranking TDS	114 consumers 51 consumers	• Grittiness sensations were still perceived with the addition of granola or peach particles. • Presence of granola changed the focus of attention from grittiness towards crunchiness.	Santagiuliana et al. (2020)
	cream cheese	-	bell pepper gel	*size* *hardness* *concentration*	RATA	73 consumers	• Addition of particles to cheese reduced creaminess and smoothness perception. • Increasing particle hardness increased chewiness, crumbliness, crunchiness, hardness, lumpiness and mouthfeel heterogeneity perception. • Increasing particle concentration increased crunchiness and bell pepper flavor perception. • Particle size did not influence sensory perception.	Santagiuliana et al. (2019)
	cream cheese	*hardness*	bell pepper gel	*hardness* *concentration*	TDS	34 consumers	• Increasing cheese hardness decreased creaminess, smoothness and melting sensations. • Increasing particle hardness decreased creaminess and bell pepper flavor sensations and increased graininess sensations. • Increasing particle concentration decreased creaminess, melting and dairy flavor sensations, and increased graininess and bell pepper flavor sensations.	(Aguayo-Mendoza et al., *submitted*)
	cheese pie	-	wheat bran ground coconut	-	FP	experienced panel (n = 20)		Marcano et al. (2015)

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Table 2 (*continued*)

2A: Sensory perception of food with added particles								
	Matrix (*varying in properties*)		Particles (*varying in properties*)		Method	Subjects	Main outcomes	Reference
			whole flaxseeds oat meal				• Presence of clearly visible dark particles resulted in particles, grainy, sandy and crunchy perception.	
2B: Sensory perception of composite foods								
	Food 1 (*varying in properties*)		Food 2 (*varying in properties*)		Method	Subjects	Main outcomes	Reference
model foods	gel layer 1		gel layer 2		TDS	10 consumers	• Texture perception of bi-layer gels was close to an average of both layers present.	Devezeaux de Lavergne et al. (2016)
commercial foods	chocolate dessert layer		chocolate dessert layer		SP	32 consumers	• Perceived complexity was related to the maximum number of salient attributes and/or the fluctuation of dominant attributes during the sequence of spoonfuls.	Palczak et al. (2019)
	vegetable		vegetable	*Ratio*	QDA	trained panel	• Sensory perception of combined vegetables was close to an average of the single vegetables present.	van Stokkom, de Graaf, Wang, van Kooten, and Stieger (2019)
	salmon		sauce	*basic taste*	DA	trained panel	• Salmon attributes (salmon flavor, fish-oil flavor) generally decreased with the addition of culinary sauces. • Addition of basic taste sauce generally increased the corresponding basic taste in the salmon.	Paulsen et al. (2012)
	chicken broth cooked rice grilled chicken		soy sauce		DA	trained panel	• Addition of an accompanying food decreased the perceived intensity of many soy sauce sensory characteristics. • Rice and chicken (solid foods) had a larger impact on the sensory characteristics of soy sauce than chicken broth (liquid food).	Cherdchu and Chambers (2014)
	bread potato		mayonnaise	*fat content* *viscosity*	DA	trained panel	• Addition of condiments increased smoothness perception, whereas typical carrier characteristics (dry, firm, fibrous) were perceived to a lesser extent. • Mayonnaise viscosity influenced sensory perception of carrier-mayonnaise combinations to a larger extent than mayonnaise fat content. • Composite foods with low fat mayonnaise were perceived as less fatty than those with full fat mayonnaise. • Composite foods with low viscosity mayonnaise were perceived as less creamy, fatty and velvety than those with high viscosity mayonnaise.	van Eck et al., 2020
	yogurt		granola	*size* *hardness* *concentration*	TDS	76 consumers	• Texture attributes crunchy and creamy dominated the beginning of each mouthful, and sweet and sticky sensations dominated the end of each mouthful. • Granola hardness and concentration largely impacted dynamic sensory perception, whereas minor effects were found for granola size.	van Bommel, Stieger, Boelee, Schlich, and Jager (2019)
	bread cracker		firm cheese cheese spread mayonnaise		PP	18 consumers	• Addition of toppings to bread or cracker led to decreased dryness and firmness perception, and increased flavor intensity perception throughout a bite. • Flavor intensities were lower for cracker-topping combinations than for bread-topping combinations.	(van Eck et al., 2019)
	bread carrot	*hardness*	mayonnaise	*fat content* *viscosity*	TDSRATA	64 consumers 66 consumers	• Carrier texture dominated sensory sensations at the beginning and end of the bite, and condiments dominated flavor sensations at the middle of the bite. • Sensations of mayonnaises were dominant at later stages of consumption when combined with harder carriers (bread, carrot).	(van Eck et al., 2019)

(*continued on next page*)

Table 2 (*continued*)

2B: Sensory perception of composite foods

Food 1 (*varying in properties*)		Food 2 (*varying in properties*)		Method	Subjects	Main outcomes	Reference
corn chips tater tots cooked rice		salsa ketchup soy sauce		TDS RATA	100 consumers 98 consumers	• Consumer sensitivity to discriminate between condiments varying in fat content and/or viscosity decreased with the addition of carrier foods. • Condiments drove flavor attribute perception (salsa, ketchup, or soy sauce flavors), while carriers drove texture/mouthfeel attribute perception. • Consumer ability to identify sensory attribute differences between the regular and sodium-reduced products decreased with the presence of the accompanying foods.	Nguyen and Wismer (2020)
cauliflower broccoli potatoes		gravy	*fat content*	DA Headspace	trained panel	• Gravy reduced sensory intensity and thereby also the less desirable vegetable flavors of cauliflower, broccoli and potatoes. This was not just a sensory masking effect, as retention of cabbage-like flavors was seen in a head space analysis.	Meinert et al. (2011)
bacon olive oil rice		banana		DA Headspace	trained panel	• Head-space release of the more lipophilic compounds of banana was suppressed, and this was more prominent for bacon and olive oil than for rice. • The paired samples were perceived different from each other, as bacon, oil and rice clearly differed in meaty and oily characteristics.	Traynor, Moreo, Cain, Burke, and Barry-Ryan (2020)
bread potato	*hardness*	mayonnaise	*fat content* *viscosity*	TI *in vivo* aroma release	trained consumers (n = 14)	• Addition of carriers to mayonnaises increased aroma release and decreased perception of aroma intensity. • Texture of the carrier foods did not significantly influence mayonnaise aroma release, likely due to the standardized chewing protocol.	(van Eck et al., *submitted*)

composite foods rather than single foods would be more realistic, this may be unpractical considering the large range of possible food combinations to be assessed, especially when also taking into account that different food combinations are used around the globe. This is also a time-consuming and expensive approach. Therefore, the recommendation with respect to sensory assessment of single foods that are rarely consumed on their own could be to perform discrimination tests within a range of commonly used accompanying foods to validate whether the new reformulated product is distinguished from the current or competitor product. The type of carrier food can differ between countries or consumer groups. As a consequence, this means that multiple food-food combinations might have to be assessed depending on the frequent consumption context of the targeted consumer group. If differences are clearly perceived, one can decide to perform rapid sensory methodologies to obtain additional information about the sensory interactions within composite foods.

Nowadays, sensory analysis is used to match new products to current market products and/or competitor products. However, the hypothesis that the new product should exactly match the reference product could be challenged. As discussed above, the perceived sensory intensity of foods decreases when accompanying foods are added. Furthermore, few studies found that consumer sensitivity to discriminate between foods declined when they were assessed together with an accompanying food (Nguyen & Wismer, 2020; van Eck et al., 2019). Thus, although sensory profiles of condiments could be discriminated when consumed by themselves, such differences were not always perceived when combined with a carrier food. This indicates that the presence of accompanying foods might distract consumer attention away from the product of interest, which might allow more flexibility in product development. This can be of particular interest in the design of health-promoting foods (e.g. low in calories, reduced fat, reduced sugar, reduced salt, increased protein, gluten-free, etc.) and sustainable foods (e.g. plant-based meat replacers, insects, etc.). The production of such foods is nowadays technically feasible, but assuring excellent sensory quality still poses a challenge. Considering frequently used accompanying foods of such healthy and/or sustainable foods might allow to develop healthier, more sustainable food combinations that are well-liked by consumers in a more affordable way.

4. Eating rate and food intake of heterogeneous foods

Food oral processing behavior (in particular eating rate and energy intake rate) has recently been linked to food intake (Robinson et al., 2014). More specifically, foods that require longer time in the mouth before swallowing (i.e. slow eating rate in g/min) have been associated with higher expected satiation (Forde, vanKuijk, Thaler, deGraaf, & Martin, 2013b), higher fullness perception (Zhu, Hsu, & Hollis, 2013; Ferriday et al., 2016) and reduced *ad libitum* food intake (deWijk, Zijlstra, Mars, deGraaf, & Prinz, 2008; Weijzen, Smeets, & deGraaf, 2009; Zijlstra, DeWijk, Mars, Stafleu, & DeGraaf, 2009; Bolhuis, Lakemond, deWijk, Luning, & deGraaf, 2011; Forde, Van Kuijk, Thaler, De Graaf, & Martin, 2013a; Brown et al., 2004; Fogel et al., 2017; Forde, Leong, Chia-Ming & McCrickerd, 2017; Lasschuijt et al., 2017; McCrickerd, Lim, Leong, Chia, & Forde, 2017).

Addition of particles to homogeneous foods is an effective strategy to decrease eating rate (g/min) (Table 1A). Slowing down food and energy intake among the general population is of relevance for public health to contribute to reduction of diet-related non-communicable diseases. The particles added to foods should be low in calories and should not increase the energy density to assure such an health benefit. In addition, although not yet investigated, healthy ingredients such as vitamins or minerals might be added to such particles to further improve the nutrition value of a food product.

The addition of condiments to solid foods is an effective strategy to increase eating rate (g/min). This knowledge is valuable when targeting foods towards the elderly population. Condiments assist saliva in bolus formation of solid carriers by decreasing bolus structure, increasing bolus lubrication, increasing bolus cohesion, or a combination of these three (Table 1B). To validate a general concept about eating behavior of composite foods, the following question can be raised: do condiments assist bolus formation of any type of solid food? As the assistance by condiments was observed for distinctly different carriers (for example dry, moisture absorbing breads and vegetables with high moisture content), it is speculated that this concept holds for any solid carrier that is combined with a condiment (e.g. pasta with sauce or meat with gravy). It is important to bear in mind that, depending on the carrier and condiment properties, the magnitude of the effect as well as the underlying mechanisms might differ between carrier foods. Largest facilitation effects are expected for dry foods, as these foods can absorb and incorporate moisture from condiments. Smallest facilitation effects are expected for very tough foods like meat, as these foods require intensive structure breakdown by the molars before swallowing regardless of a small increase in lubrication by condiments.

Properties of single foods can be changed to achieve either a faster or slower eating rate of composite foods, which is known to influence food intake. Practical guidelines to modify eating rate of composite foods are summarized in Fig. 2. The current literature indicates that various strategies can be applied to reduce eating rate and subsequent intake, such as (1) to increase hardness of the food matrix or food particles for heterogeneous foods that contain particles, (2) to reduce the fat content or increase the viscosity for (liquid-like) spreads, dressings or sauces, or (3) to increase the hardness or to reduce the size of food pieces for (solid-like) bread, vegetables or meat. Vice versa, to increase eating rate and subsequent intake, for example among the elderly population, one can consider to (1) to reduce hardness of the food matrix or food particles for heterogeneous foods that contain particles, (2) to increase the fat content or decrease the viscosity for (liquid-like) spreads, dressings or sauces, or (3) to decrease the hardness or to increase the size of food pieces for (solid-like) bread, vegetables or meat.

Only few *ad libitum* intake studies have been performed with composite foods with systematically varied food properties. For example, mashed lunch meals led to higher overall intake than whole meals (Forde et al., 2013a). Bolhuis et al. (2014) assessed intake of hamburgers (bread, meat, tomato, ketchup) and rice salads (rice, vegetables) varying in hardness (hard/soft bread, raw/cooked vegetables). Harder composite foods led to slower eating rate and a lower energy intake than the soft versions (Bolhuis et al., 2014). Mosca et al. (2019) assessed intake of yogurt with granola while varying granola particle size (large/small). Smaller granola particles led to slower eating rate and lower intake than the larger particles (Mosca et al., 2019). Recently, van Eck et al., 2020 assessed *ad libitum* snack intake of crackers varying in shape (flat squares/finger-shape sticks) with cheese dip. Both eating rate and cheese intake were higher for the flat squared crackers, as a larger amount of cheese was scooped with flat squared than finger-shape crackers (van Eck et al., 2020). Apparently, single food properties can be used to modify eating rate and thereby *ad libitum* intake of composite foods.

5. Knowledge gaps and future perspectives

This is the first review that summarizes our understanding of oral processing behavior, sensory perception and intake of heterogeneous foods. This review indicates that properties of either food components can be used to alter oral processing behavior, sensory perception and intake of heterogeneous foods, mostly investigated for single bites within a laboratory setting. Next steps should involve studies that investigate food properties that are yet underexplored (Section 5.1), validation of the present results within meals and diets (Section 5.2), and validation of the present results targeted towards specific consumer groups (Section 5.3).

5.1. Underexplored composite food properties

Large modifications of food texture (for instance fruit vs. fruit juice) are well-known to result in considerable changes in eating rate and food intake behavior. However, such changes are clearly perceived by consumers, and this lowers the potential of the food being well-accepted. For that reason, future research should investigate the influence of subtle modifications in food properties on oral processing behavior, intake and sensory perception of composite foods. In this context, it would be interesting to investigate some less explored textural properties such as variations in stickiness, brittleness or lubrication properties. Recently, it was demonstrated that modification of lubrication properties of composite food gels allowed to lower snack intake (Krop, Hoebler et al., 1998). The effect of lubrication properties of foods on oral behavior and food intake should therefore be explored further.

Variation in food shape instead of food texture might be an advantageous strategy, in particular because this strategy does not require food reformulations (thereby assuming unaffected consumer perception) and can be applied relatively easily by food manufacturers. Although the underlying mechanisms are not well understood, it can be expected that food shape can influence eating behavior via different routes, including (1) consumption effort (from package/plate/bowl to mouth) and (2) chewing effort (from bite to swallow). Firstly, in case of consumption effort, consumers are thought to apply a certain habitual consumption effort (i.e. reaching for a piece, taking a bite). Indeed, van Eck et al., 2020 showed that consumers took a similar number of cracker bites among sessions. In addition, total intake was lower when foods were served as multiple small pieces compared to one larger piece (Goh, Russell, & Liem, 2017; Liem & Russell, 2019; Weijzen, Liem, Zandstra, & de Graaf, 2008), likely because consumers had to reach for their food more often. Secondly, in case of chewing effort, some shapes require higher chewing effort in mouth to form a safe-to-swallow bolus. For instance, carrots cut julienne required more chews until swallowing than carrots cut into cubes (van Eck et al., 2019). Similarly, yogurt with many small granola pieces required higher chewing effort leading to lower intake than yogurt with few large granola pieces (Mosca et al., 2019). In both cases, more time and saliva were required to adhere the larger number of smaller pieces into a cohesive safe-to-swallow bolus. Although these few studies suggest that a variation in food shape can affect oral processing behavior and food intake, the role of food shape is still an underexplored topic. Further research is needed to validate a general theory about the influence of food shape on oral processing behavior, intake and sensory perception.

5.2. From single bite to meals and diets

This review shows that even small modifications of only one food can modify oral processing behavior, food intake and sensory perception of composite foods in a laboratory setting. A next step would involve studies investigating the role of single food properties on oral processing behavior, intake and perception of a complete meal, i.e. composite foods that are composed of more than two single foods, in a real life setting. As eating rate is a main determinant of food intake behavior, dietary interventions comparing a "fast diet" versus "slow diet" will be of interest to validate the recent composite food findings into daily life practices and public health applications. Recently, higher *ad libitum* intake (~500 kcal/day) was reported for ultra-processed diets with a high eating rate (37 g/min) compared to unprocessed diets with a low eating rate (30 g/min) (Hall et al., 2019). In this context, one can argue that a difference in eating rate rather than industrial food processing was responsible for the difference in intake (Forde, Mars, & De Graaf, 2020). Therefore, clean dietary interventions investigating which food properties within the diet affect eating rate and food intake are required.

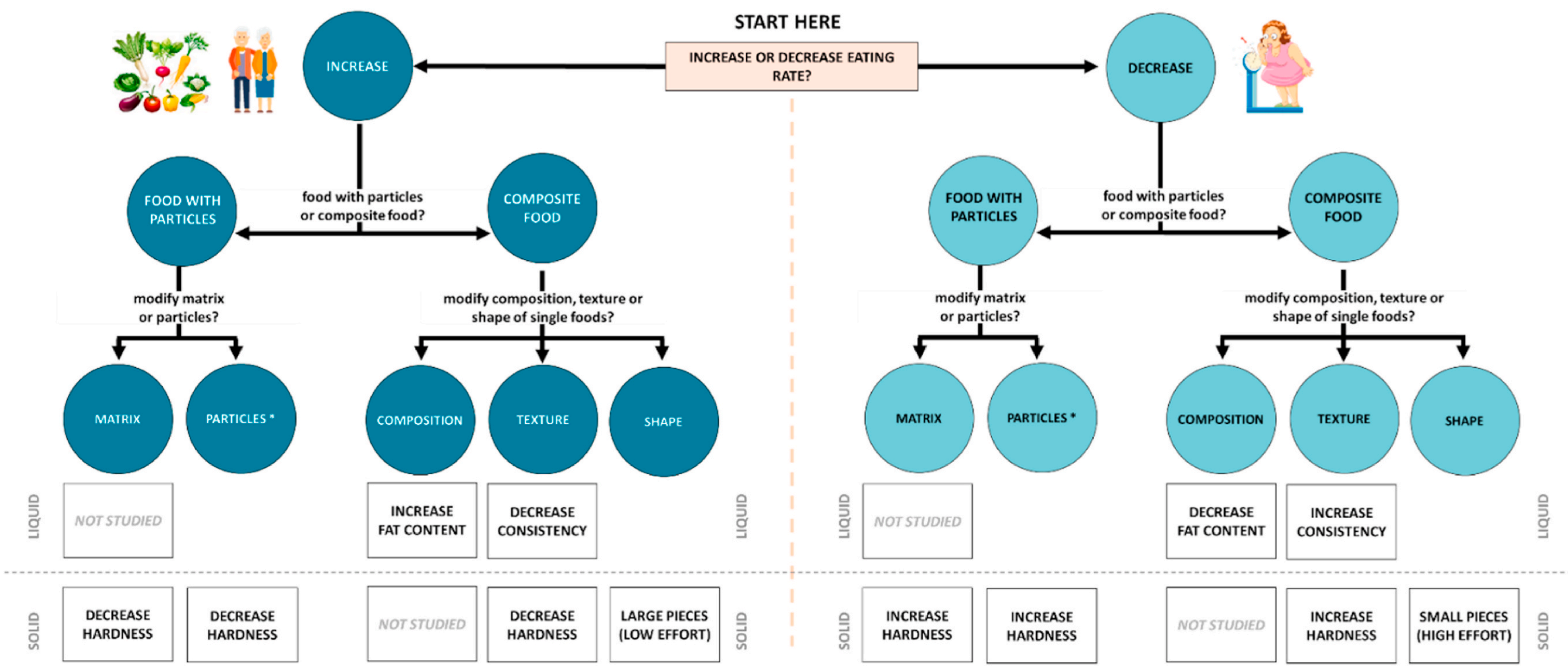

Fig. 2. Decision chart showing how the eating rate of foods with particles or composite foods can be increased (left side) or decreased (right side) by changing single food properties.

5.3. Personalized food design?

Oral processing behavior is known to be influenced by consumer characteristics such as gender, age and ethnicity (Ketel et al., 2019). Nowadays, the elderly population is growing; and prevalence of malnutrition is frequently observed among the elderly (Hickson, 2006; Fávaro-Moreira et al., 2016). Ageing is known to cause decline in sensory functions, changes in salivary flow and composition, tooth loss and/or reduced jaw muscle strength, which in turn alter eating capability. Such a decrease in eating capability leads to reduced food intake, and consequently an increased risk of malnutrition Ikebe et al, 2012 (Fontijn-Tekamp, Van der Bilt, Abbink, & Bosman, 2004; Vandenberghe-Descamps et al., 2016). Practical approaches to increase food and nutrient intake among elderly are therefore required. The present review highlights that the addition of liquid or semi-solid foods (such as condiments) to solid foods is an effective strategy to increase eating rate (g/min) and consequently potentially intake. This knowledge is valuable when targeting foods towards the elderly population to ensure healthy ageing.

With regards to personalized food design, more attention should be paid to inter-individual variation in eating rate (slow vs. fast eaters). Within a demographical group, eating rate largely depended on personal habits, leading to significant changes in bolus formation and sensory perception of single foods (M. Devezeaux DevezeauxdeLavergne, Derks, Ketel, deWijk, & Stieger, 2015). In addition, such habitual eating strategies are consistent within individuals (i.e. those who eat one meal faster, also eat other meals faster) (McCrickerd & Forde, 2016; Robinson et al., 2014) and constant over time (i.e. those who eat faster at young age, still eat faster several years later) (Fogel et al., 2018). Now, it would be relevant to understand how inter-individual variation in eating rate affects oral processing behavior, intake and sensory perception of composite foods. We speculate that slow eaters are more sensitive to small modifications in single food properties than fast eaters. Consequently, the suggested approach to change single food properties to modify composite food intake might be more effective in slow chewers than fast chewers, as slow eaters may be aware of changes in reformulated foods whereas fast eaters are not. Whether changing composite food properties is an efficient strategy to slow down fast eaters should still be validated.

Differences in combination behavior can be observed among consumers. For instance, some consumers prefer to add a little bit of sauce to their dish whereas others like to add plenty of sauce. This can result in large differences in oral processing behavior, intake and sensory perception between consumers. Such inter-individual differences in carrier:condiment weight ratios should therefore be taken into consideration in future research on composite foods to for example tailor portion sizes.

6. Conclusions

The increasing demand for practical approaches to regulate food intake while maintaining excellent sensory characteristics represents an opportunity, yet also a challenge. Properties of single foods can be used to alter eating behavior and sensory perception of composite foods. With respect to eating behavior, relatively small changes in food properties (changing viscosity, hardness or dimensions) can already have an effect on eating rate. Physical changes in structure can be used to reduce overconsumption or to increase healthy food intake without having to change food formulations or nutrient composition to a large extent. We conclude that sensory perception of composite foods is complex, and sensory characteristics of one food are influenced by the specific properties of the other food present. Consumer sensitivity to discriminate between foods declined when these were assessed together with an accompanying food. This was not due to reduced delivery of aroma compounds into the nasal cavity, indicating that cognitive effects such as distraction play a role in sensory perception of composite foods. This supports the idea that both food design and cognitive factors should be used to modulate consumer perception. These findings can be of particular interest in the design of health-promoting foods.

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* The impact of particle concentration depended on the matrix. Increased particle concentration increased oral processing time of yogurt (semi-solid) but not of cheese (soft solid).

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