Food Structure 13 (2017) 1–12

Contents lists available at ScienceDirect

Food Structure

journal homepage: www.elsevier.com/locate/foostr

Designing foods for satiety: The roles of food structure and oral processing in satiation and satiety

Caroline L. Campbell, Ty B. Wagoner, E. Allen Foegeding*

Department of Food, Bioprocessing and Nutrition Sciences, Box 7624, North Carolina State University, Raleigh, NC, 27695-7624, United States

ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 26 July 2016
Accepted 30 August 2016
Available online 2 September 2016

Keywords:
Food structure
Texture
Oral processing
Satiation
Satiety

ABSTRACT

Food consumption is determined by a range of factors that contribute to satiation, which ends a meal, and satiety, which determines time between meals. Food structure and texture contribute to satiation and satiety; however, the precise mechanisms are not fully established. The time required for oral processing has been shown to influence satiation/satiety, but the roles of physiological elements of oral processing, such as muscle activity, jaw movement, and tongue movement, remain to be established. Relationships among food structure, texture, oral processing, and satiation/satiety are discussed in reference to designing foods to maximize the contribution of food structure to satiation/satiety.

Contents

1. Introduction

A growing world population combined with global climatic changes has urged society to critically evaluate the agriculture-food continuum. The relatively new concept of "food security" is a primary consideration in order to feed 9 billion people by 2050 (Godfray et al., 2010). Ideally, this would be accomplished by sustainable increases in agricultural production with foods that supply the ideal amount of nutrients – preventing the problems of insufficient nutrients and also inhibiting the over consumption of nutrients. The latter is an immediate problem manifested in obesity rates of 36% in the US and 13% globally (Weight-Control

* Corresponding author.
E-mail address: allen_foegeding@ncsu.edu (E. A. Foegeding).

http://dx.doi.org/10.1016/j.foostr.2016.08.002
2213-3291/

Information Network, 2012; World Health Organization, 2015). While the causes of obesity are complex, one approach to curb obesity is to develop tactics that decrease our daily consumption of food. Our food preferences and consumption habits can be better understood by analyzing the roles played by food structure and individual nutrients, which are driven by our choices in agricultural production.

A general food consumption model consists of three daily meals and possible intermittent snacks. The cessation of a meal occurs when a point of *satiation* is reached, whereas the time between meals is a measure of *satiety*. The amount of food consumed during a day, controlled in part by satiation and satiety, should supply nutrients responsible for health and energy in balance with energy expenditure. This is a simplistic representation of a very complex process; nonetheless, it is clear that foods that increase satiation and satiety should be helpful in controlling food intake. Multiple variables influence the onset of satiation and satiety; therefore, designing foods that provide early satiation and enduring satiety requires the consideration of overlapping interactions among food composition, food structure, oral processing, and dynamic sensory perception as well as psychological inputs such as environment and hedonic liking.

In the context of food consumption from mouth through digestion, one could hypothesize that perceptions of satiation and satiety are formed by: 1) specific types of food molecules, 2) specific food structures and their transformations during oral processing, 3) physiological oral processing activities required for bolus formation, 4) oral processing time, or 5) a combination thereof. Though psychological inputs are also of great importance, the goal of this review is to discuss the role of food structure and oral processing in satiation/satiety and to evaluate the current level of mechanistic understanding. Recent reviews have addressed the relationships among food structure, oral processing, and sensory perception (Foster et al., 2011; Koç, Vinyard, Essick, & Foegeding, 2013; Pascua, Koç, & Foegeding, 2013; Stieger & van de Velde, 2013), sensory perception and satiation/satiety (de Graaf & Kok, 2010; de Graaf, 2012), and chewing, appetite, food intake, and gut hormones (Miquel-Kergoat, Azais-Braesco, Burton-Freeman, & Hetherington, 2015). We build on those reviews and add the potential contribution of physiological processes associated with oral processing.

2. Building food structure

In order to discuss structural breakdown and changes during oral processing (and how they may influence psychological and physiological aspects of perception), it is important to first consider the nature of food structure and texture. From the perspective of states of matter, van Vliet, van Aken, de Jongh, and Hamer (2009) classified foods as fitting into broad categories of: fluids, semisolids, soft solids, and hard solids. While universal delineations among categories are difficult, a first approximation is that: fluids flow and have minimal or no yield stress (e.g., beverages); semisolids are fluid-like, have a high yield stress, and deform or break without fracturing into pieces (e.g., pudding, yogurt, and bananas); soft solids fracture into pieces but without sound (e.g., cooked egg white, some cheeses and processed meats); and hard solids fracture into pieces and emit sound during fracture (e.g., crackers, toast, nuts, apples, and carrots). These differences in overall physical properties are due to elements of food structure. The assembly of molecules into food structures occurs by biological processes (i.e., plant and animal cells and tissues), food processing (e.g., processed cheese, gummy bears, bread, pasta, and tofu), or a combination of biological processes and food processing (e.g., whipped cream, pepperoni, and orange juice). Food structures can also be composed of multiple biological and processed components, such as yogurt containing oats or fruit pieces.

The diversity of food structures provides for culinary delight but greatly complicates our understanding of the contribution of structure to satiation/satiety. Foods based on biological structures, such as apples and carrots, are useful because they are part of a normal diet; however, they exhibit inherent variability among samples. This cannot be adjusted and can only be controlled by rigorous selection. In contrast, the structure of foods formed during processing is more easily controlled. Model foods are designed as simplified food analogs that reflect key elements of normal food. For example, biopolymer gels have been used extensively as models for soft solid foods (Çakir, Daubert et al., 2012; Çakir, Vinyard et al., 2012; Devezeaux de Lavergne, van Delft et al., 2015; Devezeaux de Lavergne, van de Velde et al., 2015; Hayakawa et al., 2014; Ishihara et al., 2011; Koç et al., 2014; Kohyama et al., 2015, 2016). However, compared to the general complexity of everyday foods, model systems may limit the interpretation of experimental results. The relative merits of different structures in investigating the contribution of food structure to satiation/satiety will be discussed in subsequent sections.

3. Food structure and oral processing

Foods can be considered a collection of molecules formed into structures that are transformed into a bolus during oral processing. Food oral processing encompasses a range of variables, including oro-sensory time (de Graaf & Kok, 2010; Haber, Heaton, Murphy, & Burroughs, 1977; Hogenkamp & Schiöth, 2013), muscle and jaw activity (Agrawal, Lucas, Bruce, & Prinz, 1998; Brown, Eves, Ellison, & Braxton, 1998; Çakir, Koç et al., 2012; Ishihara et al., 2011; Koç et al., 2014; Peyron, Lassauzay, & Woda, 2002; Smit, Kemsley, Tapp, & Henry, 2011), tongue behavior (de Wijk, Engelen, & Prinz, 2003; de Wijk, Polet, Bult, & Prinz, 2008), bite size (Bolhuis et al., 2014; de Wijk et al., 2008; Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013; Spiegel, 2000), and palatability (Bellisle, Guy-Grand, & Le Magnen, 2000; de Wijk et al., 2008). Oral processing parameters are directly influenced by, and adjusted to accommodate, changes in food texture throughout the chewing sequence (Hiiemae et al., 1996; Mioche, Bourdiol, Martin, & Noël, 1999; Peyron et al., 2002). Additionally, texture perception, which influences expectations of satiety, is a dynamic process influenced by oral processing (Hiiemae, 2004). Thus, the interrelations among food structure, structural breakdown during oral processing, and sensory perception of texture are all important in understanding the effects on satiation and satiety.

In the simplest sense, oral processing can be considered the specific movements of the tongue and jaw – and the muscle activities required for these movements – during manipulation of food in the mouth. These motions are controlled by a central pattern generator in the brain stem (Yamada, Yamamura, & Inoue, 2005); thus, feedback mechanisms regulate the oral process and adjust to changes in food texture and sensory perceptions. Lund (1991) divided the oral process into three phases: preparatory cycles, particle reduction cycles, and pre-swallowing cycles (Lund, 1991). These divisions are reflected in the transport model of Hiiemae and Palmer, which describes the three dynamic stages associated with mastication (Hiiemae & Palmer, 1999). Stage I occurs immediately after a bite of food, where the bite is moved by a series of low amplitude, simple movements of the jaw without occlusion of the teeth. The duration of this step is dependent on the textural attributes of the food material. During stage II, the bite is transformed into a bolus through comminution of the material combined with lubrication from saliva. Depending on the type of food material, jaw movement during this phase is often rhythmic with discrete opening, closing, and occlusal phases. Textural