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Selection in mixtures of food particles during oral processing in man

Hilbert W. van der Glas[a,b,*], Esther H.-J. Kim[a,1], Anis Z. Mustapa[a,2], Wijdan R. Elmanaseer[a]

[a] The Dental School, University of Dundee, Dundee, Scotland, UK
[b] Department of Otorhinolaryngology and Head & Neck Surgery, University Medical Center Utrecht, Utrecht, The Netherlands

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ABSTRACT

Objectives: Two processes underlie food comminution during chewing: (1) selection, *i.e.* every particle has a chance of being placed between the teeth and being subjected to (2) breakage. Selection decreases with particle number by saturation of breakage sites, and it depends on competition between smaller and larger particles for breakage sites. Theoretical models were tested which describe competition between various sizes X. In the one-way model, small particles cannot compete with larger ones because of their smaller height. In the two-way model, small particles may compete when piled between antagonistic teeth.

Design: Five subjects participated in one-chew experiments on cubes made of Optosil®. The critical particle number ($n_c(X)$) at which saturation starts, and the number of breakage sites ($n_b(X)$) were determined by varying particle numbers (n_X) for single-sized cubes of 1.7-6.8 mm. Using $n_c(X)$ and $n_b(X)$, the models predicted relationships between number of selected particles ($n_s(X)$) and n_X in one-chew experiments using simple mixtures with only two sizes. A fixed number (mean 6 or 26) of larger cubes (X = 6.8 or 3.4 mm) was mixed with various numbers (16–1024) of smaller cubes (X = 4.8, 2.4 or 1.7 mm), thus varying the factors X, n_X, and possible particle piling (for $X < 4$ mm).

Results: The one-way model was largely followed with small numbers of smaller particles and the two-way model with large numbers.

Conclusions: The two-way model applies to chewing a food which yields a loose aggregation of different-sized particles following an initial phase, whereas other circumstances may be favourable for the one-way model. As conditions of a food bolus can be approached by embedding hard Optosil particles in a soft medium, the models will, apart from dentistry, be of interest for controlling flavour release in food engineering.

1. Introduction

One of the major functions of chewing is to prepare food for safe swallowing by mixing it with saliva and by grinding large particles into small fragments. Due to this fragmentation, the surface area of the food is increased yielding a more efficient breakdown by enzymes in the mouth and later in the gastrointestinal tract.

The food comminution in human mastication has gained a great deal of attention in many fields of research. In the field of dentistry, chewing efficiency/performance of subjects with a natural dentition has been compared with that of patients wearing dentures for examining the extent to which chewing function is restored by dental prostheses and implants (Trulsson et al., 2012; van der Bilt, 2011). The relationship between dietary demands and tooth morphology is of interest from an evolutionary point of view (Lucas, 2004). Furthermore, food comminution has the interest of the food industry as it facilitates and influences the release of flavour (Hutchings et al., 2012; Kim et al., 2015).

As in industrial comminution processes (Epstein, 1947), the breakdown of solid food particles during chewing can be considered as the composite result of two underlying mechanisms: *i.e.* selection and breakage (Lucas & Luke, 1983; van der Glas, van der Bilt, Olthoff, & Bosman, 1987). Every chewing cycle begins with selection, in which food particles have a chance to be placed between the teeth in such a way that they are at least damaged, if not broken by the subsequent breakage process. For any particle size, the selection chance can be defined as the weight of fragments with respect to the total weight of damaged and non-damaged particles from that size. During a sequence of rhythmic chewing movements of which the basic muscle activity is generated by a central pattern generator in the brainstem (Lund, Kolta, Westberg, & Scott, 1998), selection of food particles will occur unconsciously rather than consciously. Variation in particle transport by

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[*] Corresponding author at: The Dental School, University of Dundee, Park Place, Dundee DD1 4HR, Scotland, UK.
E-mail addresses: h.vanderglas@dundee.ac.uk, hwvanderglas@hotmail.com (H.W. van der Glas).

[1] [c]Permanent address: The New Zealand Institute for Plant & Food Research Limited, Lincoln, New Zealand

[2] [d]Present address: Department of Prosthodontics, International Islamic University Malaysia, Kuantan, Malaysia

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the tongue and in the engagement by the teeth will ensure a highly randomized distribution of where a particle finally engages between antagonistic teeth (van der Glas, van der Bilt, & Bosman, 1992).

Two categories of factors influence the selection as well as the breakage process, *i.e.* subject-related anatomical and physiological factors, and food-related factors. The selection process will depend upon factors such as the action of the tongue and the cheeks, the tooth shape, the total occlusal area of teeth, the adhesive influence of saliva (anatomical and physiological factors), and the particle number and size (food-related factors; Lucas, 2004; van der Glas et al., 1992;). Breakage is the process by which selected particles are fractured between the teeth into fragments of variable number and size. Breakage depends upon the tooth shape, the amount and the coordination of the muscle activity (anatomical and physiological factors), the firmness of the food, and the particle size and shape (food-related factors; Lucas, 2004; van der Glas et al., 1992).

As oral structures including the dentition are evolutionary adapted to the available food, describing and explaining relationships between the selection process and food-related factors is of primary interest (Lucas, 2004). Chewing on colour-and-form labelled particles of various size has shown that the selection chance $S(X)$ increases with the particle size X according to a power function (Lucas & Luke, 1983; van der Glas et al., 1987), hence: $S(X) = v.X^{w}$ $(0 \leq S(X) \leq 1)$. Regardless of the subject examined, the exponent w is always larger than one for a food which forms a loose aggregation of particles during chewing; w varied within a range from 1.6 to 2.6 across both studies. The variation in w-values is related to inter-subject differences in anatomical and physiological factors. However, values of w which are consistently larger than one indicate that the selection chance always increases more than proportionally with particle size. Hence, larger particles are more easily collected by the tongue and/or captured between antagonistic teeth than smaller ones in the natural chewing process.

Apart from particle size, the selection chance also depends upon the particle number as a food-related factor. The number of breakage sites which are available on the teeth, is limited because of a limited number of antagonistic teeth. Hence, the selection chance will be smaller the more the teeth become saturated with particles (van der Glas et al., 1992). Since the same tooth surface is used to break particles of different size, the sites at which large particles are broken overlaps greatly with the sites at which small particles are broken. Thus, small particles and large ones must compete with each other for breakage sites.

A theoretical model has been developed to describe selection of single-sized particles as a function of their number, and this model has been confirmed in one-chew experiments for a range of particle sizes of 1.2-9.6 mm (van der Glas et al., 1992). For any particle size, the number of selected particles increases initially approximately linearly with the number of particles offered and then gradually levels off when the available number of breakage sites becomes saturated with particles. Chewing yields mixtures of particles in the mouth with various sizes. The model that describes the selection of single-sized particles has been extended to mixtures to describe how different-sized particles mutually compete for the breakage sites (van der Glas et al., 1992). Two variants of the model for mixtures are: (1) the one-way interaction model in which large particles hamper the selection of smaller ones without the reverse occurring, and (2) the two-way interaction model in which a two-way competition occurs between large and smaller particles. Piling of small particles at the engagement of the food between antagonistic teeth is then essential for enabling small particles to compete with larger ones for the breakage sites.

The aim of the present study was to test the theoretical selection models for particle mixtures experimentally. In one-chew experiments, relationships were determined between number of selected particles and the number of offered particles while being part of a simple mixture which included only two sizes. The factor of possible particle piling was varied by choosing appropriate particle sizes. Observed relationships between number of selected particles and number of offered particles were compared with those as predicted by the two selection models for mixtures.

Table 1
Procedure of testing theoretical selection models for particle mixtures.

Stage (1): Obtaining values of particle affinity and number of breakage sites for each subject: One-chew calibration experiments using 5 cube sizes X (1.7, 2.4, 3.4, 4.8 and 6.8 mm) and various numbers of cubes per size (cf. section 2.4. 'One-chew Experiments' f.);

For each size X, determination of the relationship between number of selected particles and number of offered particles, with particle affinity, $O_1(X,1)$ and number of breakage sites, $n_b(X)$ as parameters in curve-fitting using the single-size selection model (Eq. (1));

Stage (2): Enhancing the accuracy of values for $O_1(X,1)$ and $n_b(X)$:

Conversion of $O_1(X,1)$ values obtained in stage (1) to values of critical number of particles, $n_c(X)$ using Eq. (3);

Curve-fitting of the $n_c(X)$ values using a power function describing the $n_c(X)$-X relationship (Eq. (11)) and determination of the function values of $n_c(X)$ for the five cube sizes used (range: 1.7-6.8 mm);

Re-conversion of the function values of $n_c(X)$ to function values of $O_1(X,1)$ using Eq. (12). Because the function values include information from five $n_c(X)$-values used in the curve-fitting with the power function, the accuracy of a function value of $O_1(X,1)$ for a particular particle size is larger than that of a single estimated value of $O_1(X,1)$ obtained in stage (1);

Curve-fitting of the $n_b(X)$ values using a power function describing the n_b-X relationship (Eq. (10)) and determination of the function values of $n_b(X)$ for the cube sizes used;

Stage (3): Predicting theoretical values of number of selected cubes in one-chew experiments with simple mixtures:

For each subject, substitution of the function values of particle affinity, $O_1(X,1)$, and number of breakage sites, $n_b(X)$, for the cube sizes used in simple mixtures (three types of mixtures, each with two cube sizes), in Eq. (5), (1)-way interaction model for selection, and in Eq. (7), (2)-way interaction model respectively;

For each model, calculation of predictions of the number of selected particles of the smaller size in a mixture (in the presence of a constant number of the larger size), as a function of the number of offered particles of the smaller size, using Eq. (5) and (7) respectively with substituted parameter values;

Also calculation of the number of selected particles within a constant number of the larger size as a function of the number of offered particles of the smaller size;

Stage (4): Testing the validity of the models of selection of particles during a chew:

One-chew experiments using simple particle mixtures;

Determination of the Mean Square Difference (MSD; Eq. (14)) between log-transformed experimental values and predicted theoretical ones of the number of selected particles. Using MSD, the validity of the theoretical models is tested statistically.

2. Materials and methods

2.1. Theoretical background

While details about the theoretical background can be found in a previous study (van der Glas et al., 1992), only main features are presented here. Table 1 shows an overview of the procedure of testing the theoretical selection models for particle mixtures.

A theoretical model describes the number of particles of any single particle size X, which is selected in a single chew, $n_s(X, n_X)$, as a function of n_X, the number of particles offered of size X,

An $n_s(X, n_X) - n_X$ relationship is given by:

$$n_s(X, n_X) = n_b(X).\left[1 - (1 - O_1(X, 1))^{n_X}\right] \tag{1}$$

in which $O_1(X,1)$ is the affinity factor for particles of size X and $n_b(X)$ is the number of breakage sites that is available for particles of size X. The factor $[1 - (1 - O_1(X, 1))^{n_X}]$ in Eq. (1) represents the fraction of the breakage sites which is occupied when n_X particles are present. $O_1(X,1)$ is the fraction of breakage sites which is, on average, occupied by the first particle that is selected by the teeth. This fraction is given by:

$$O_1(X, 1) = S_1(X, 1)/n_b(X) \tag{2}$$

in which $S_1(X,1)$ is the chance of the first particle of being selected to subsequent breakage. $O_1(X,1)$ is thus the selection chance of a single particle per breakage site, and is by definition considered as a measure