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Mechanistic model to understand *in vivo* salt release and perception during the consumption of dairy gels

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Abstract

The objective of this study was to develop a model to simulate salt release during eating. Salt release kinetics during eating were measured for four model dairy products with different dynamic salty perceptions. A simple *in vivo* model of salt release was developed to differentiate between the contribution of the individual and of the product to salt release. The most difficult model parameter to determine or predict is the evolution of the contact area between the product and the saliva. Fitting the model to the experimental data allowed us to show that the subject's masticatory performance and product structure determined the contact

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area between the product and the saliva generated by mastication. Finally, the role of release dynamics on sensory time-intensity profiles is discussed.

Keywords: mechanistic, cheese, temporal, sensory, NaCl

1 Introduction

Reducing salt content in food is a major concern for public health authorities worldwide and a major challenge since it often induces a reduction in sensory quality and technological properties of food products concerning their functionality and their safety. Understanding the mechanisms involved in perception could help to formulate products that satisfy both nutritional and sensory criteria.

During food consumption, salt must be released from the product and diluted in the saliva to reach the taste receptors located on the tongue and, thus, induce salty perception. Understanding and modeling taste compound release during the mastication of "solid" foods is a challenging task due to the complexity of the phenomena that occur in the mouth: dilution by saliva, mastication, temperature modification, etc.

Few studies have attempted to measure the *in vivo* salt release kinetics during the mastication. Jack et al. (*1*), Davidson et al. (*2*) and Neyraud et al. (*3*) monitored conductivity during eating with electrodes placed in the interdental space between the incisors. However, conductivity probes placed in the mouth can disturb normal mastication behaviour. A non-invasive technique consisted in sampling saliva from the tongue at different moments during the eating process in order to analyse the components present in the saliva (*3*–*5*).

Most of the descriptors (initial slope, maximal concentration, etc.) extracted from these kinetics can be statistically related to a subject's physiological parameters such as saliva flow rates or masticatory performance, as well as to product composition (*4*, *5*). However, these statistical approaches are global and do not offer the possibility to understand the contribution of the product and the individual to stimuli release. Modeling was shown to be an effective tool for understanding, quantifying and predicting

the influence of each parameter on release kinetics.

The first model of flavour release during the consumption of solid products was developed by Harrisson et al. (*6*). The transport of aroma compounds across the food-saliva interface was described by the interfacial theory of mass transfer. Saliva flow, mastication and swallowing were incorporated into the model. Mastication was modeled by selection and breakage functions to generate particle size distributions but was independent of physiological parameters (*6*). Wright and Hills (*7*, *8*) calculated function parameters from the individual's mastication pattern that was acquired with electromyography and spit out experiments. Detailed knowledge of the mastication process is important to predict particule size distribution and, consequently, the contact area between the product and the saliva and the product and the air (*6–8*). Food fragmentation can be modeled from empirical laws fitted to experimental data obtained from spit-out experiments (*9*, *10*) or by statistical models that consider mastication as a selection and breakdown process (*6*, *7*, *11*, *12*). Another approach was developed by de Loubens et al. (*13*). In their study, salt release kinetics were measured after compression of model dairy products. The salt release kinetics from fragmented products were modeled. To model salt release during mastication (< 40 s), they show that knowledge of the size distribution of the particles is unnecessary. The main parameter that has to be known is the evolution of the contact area between the particles and the saliva. These considerations considerably simplify the physical formulation of the model and reduce the number of variables that are often difficult to experimentally determine. The main difficulty in predicting the contact area is due to the fact that it depends a priori on the subject's masticatory behaviour and on the fracture mechanics and reagglomeration of food, which depends on food structure and composition.

The objective of the present study was to develop a model of salt release during the consumption of gel food products and to determine the influence of the product and physiological parameters on the evolution of the product/saliva contact area on the basis of experimental *in vivo* salt release kinetics.

Firstly, four model dairy products with different compositions were chosen because

they had already been extensively characterised in terms of rheology and texture (*14*), as well as in terms of bolus formation (*15*) and breakdown properties (*13*). In this study, their sensory dynamic characteristics were determined. An experimental method was used to measure salt release kinetics during eating. The panellists were characterised on a physiological basis. A simple model of salt release was then developed based on the main assumption that generation of the contact area between the product and the saliva governs salt release. This assumption has already been validated by de Loubens et al. (*13*). On the basis of the experimental data and the model, the specific contributions of the product and of the panellist to this parameter were studied and related to experimentally measurable parameters. Finally, the role of release dynamics on sensory time-intensity profiles is discussed.

2 Materials & Methods

2.1 Sample preparation

Model dairy products were prepared as described by Sain-Eve et al. (*16*): ultra-filtrated skim milk retentate powder PL60 (Triballat, Noyal-sur-Vilaine, France), anhydrous milk fat (Corman, Goe, Belgium) and sodium chloride (Prolabo, France) were mixed and gelled by addition of rennet. Four model cheeses (Table 1) were studied in the present work, varying only in their fat content (0 or 40%, dry basis) and their retentate powder concentration (150 or 250 g/kg). The other composition parameters remained constant: salt content (1% w/w) and pH-value (6.2). Throughout the paper, products will be referred to according to the following code: PL 60 concentration (150 or 250 g/kg) / fat content (0 or 40%).

These products had already been extensively characterised in terms of mechanical properties by (*14*). Figure 1 shows a typical stress-strain curve obtained during product compression (experiments carried out in (*14*)). For all the products, this curve presented a maximum that corresponds to the fracture initiation. In this study, we calculated two parameters: (i) breakdown energy E_b (in kJ/m^3) defined as the energy necessary to break

up the product at 80% of strain and (ii) fracture initiation energy E_{fi} (in kJ/m^3) defined as the energy necessary to initiate the fracture in the product.

2.2 Sensory analysis

Sixteen volunteer panellists were recruited and trained for the evaluation of salty perception and for time-intensity (TI) methodology. The four training sessions were focused on salty perception in water and in model cheeses (identification, ranking, intensity evaluation and temporal perception), and on software training (using Fizz software). During the product evaluation, the four products were tested in a session and two replicates for the session were performed. The samples were presented monadically. The presentation orders of the products were defined using an orthogonal Latin square. The samples were coded with three-digit random numbers and 5 g of sample was served at 15°C. Panelists were asked to rinse their mouth with water and to eat a piece of apple between each sample. The tests were run under white light conditions. For each evaluation, the panellists clicked on the left extremity of a horizontal unstructured scale (corresponding to no sensation) when they put the product into their mouth. Panellists were then asked to move the cursor along the scale as the sensation evolved until the end of the perception.

For each sample, average TI curves were drawn by averaging the data at each time across the 16 subjects and the two replicates. No specific averaging method was used.

2.3 Physiological measurements

Masticatory performance

The masticatory performance M_sP of each subject was measured. Each subject was instructed to chew standardised cylinders (weight: 3 g; heigth: 1.8 cm; diameter: 1.4 cm) of Optosil silicone dental (Perrigot et Cie, Dijon, France) during 20 masticatory cycles. They were then asked to spit the sample onto a filter paper. The pieces of the chewed sample were spread on paper and dried in an oven for 1 h at 75°C. The particles were then separated using a sieve with a 4-mm mesh. The masticatory performance of each

subject over 20 s was defined as the amount of sample that passed through the sieve over the amount of chewed sample. This procedure was repeated three times.

Stimulated saliva flow rate

Stimulated saliva flow rates Q_s were measured for each panelist. Panelists chewed 0.5 g of parafilm (American National Can, Menasha, WI, USA) without swallowing and spit out their saliva at 30 and 60 s. The saliva flow rate is obtained by dividing the mass of saliva collected by the time of the experiment.

2.4 Experimental measurement of salt release kinetics during eating

Saliva sampling

Eight panellists were recruited for this study. Before the product was consumed, the saliva was stimulated with parafilm. Saliva sampling during the consumption of 5 g of product consisted in the application of a Whatman filter paper for 1-2 seconds on the tongue surface. A first sampling was done at time $t = 0$ before product introduction into the mouth. A second sampling took place just after the time of the first swallowing event t_s and the four others at t_s+10 s, 40, 60 and 80 s (from t_2 to t_5). Before each sampling, panelists were instructed to swallow and to clear their tongue with their teeth. Each piece of filter paper was weighed before and after sampling in order to determine the quantity of saliva sampled. Four replicates per product and per panelist were performed.

Measurement of salt concentration in saliva

Salt concentration in saliva was measured with a conductivity probe (Heito, France) that was calibrated at 20°C with aqueous NaCl solutions prepared with deionised water. In the present work, the concentrations are given in equivalent g/L of NaCl .

In addition to NaCl, model cheeses contained other solutes such as potassium, calcium, phosphates, citrates and lactates (*17*). Moreover, saliva contains naturally different

solutes (*3*) whose concentrations differ depending on whether the saliva is stimulated or not. This is the reason why saliva was stimulated with parafilm before product consumption and its conductivity was measured just before eating to take this value into account. In the present paper, we defined "salt" as all the species that contribute to the conductivity signal.

The piece of filter paper used for saliva sampling was placed and shaken in 15 mL of deionised water during 15 min at 20°C. The conductivity of the solution was measured. Given the dilution rate, the conductivity of the saliva sample was determined. The filter paper contribution to the conductivity signal was measured beforehand and subtracted from the global signal.

2.5 Mathematical model

2.5.1 Hypothesis of the developed model

Mass transfer theory During mastication, the product is fractionated into little pieces and its contact area with saliva increases. To model flavour release from a chewed bolus, Harrison et al. and Wright and Hills (*6–8*) calculated the particle size distribution generated by mastication. Modeling the particle size distribution is of minor interest except to calculate the contact area. In fact considering that the mastication time (~10 s in the experiments) is relatively short compared to the characteristic time of release, the size distribution is expected to have a low impact on the kinetics. For example, considering that salt release is due to a Fickian diffusion ($D \sim 10^{-9} - 10^{-10} m^2/s$, (*14*, *18*)), the product thickness where the concentration significantly decreases is given by $\sqrt{4Dt}$ (*18*) and, consequently, is approximately 0.06-0.2 mm. Considering a melting surface phenomenon, the thickness is given by tv where v is the velocity of the surface layer melting ($v \sim 3.10^{-5} m/s$, (*8*)) that is approximately 0.3 mm. This thickness range is relatively small compared to the median particle size measured just before swallowing, which is approximately 2.8 mm for carrots and 1 mm for peanuts (*19*, *20*). Therefore, the salt concentration in the bulk product has not yet the time to significantly decrease and remains homogeneous. Hence, the time of mastication is sufficiently short to not

take the particle size distribution into account. Knowledge of the saliva/product contact area is sufficient to satisfactorily represent the mass transfer phenomena and to consider that the concentration in solutes inside the product is homogeneous. These considerations considerably simplify the mastication model formulation and reduce the number of variables required for the model that are often difficult to determine experimentally. Finally, as shown in Figure 2, we can assume that the release of solutes can be described by a mass transfer coefficient k_p (m/s) and that salt concentration in the bulk product C_p can be considered uniform during the short residence time of the product in the mouth. For short times (<40s), this type of model has already been successfully validated on salt release kinetics from the same dairy gels reduced into small particles by standardised compression (*13*).

Evolution of the contact area between product and saliva and of the volume of saliva Bolus volume increases with the saliva flow rate. At each swallowing event, part of the product and of the saliva transit to the pharynx. Hence, product and saliva volumes and contact area instantly decrease. Between two swallows, saliva volume increases linearly with the saliva flow rate. The variations of contact area $A(t)$ and of saliva volume $V_s(t)$ are shown on Figure 2-b and c. The initial area A_0 is given by the initial geometry of the sample. We consider that before the first swallowing event, the evolution of the contact area between product and saliva is linear. Firstly, the products being fragmented during the course of the mastication, its contact area with saliva increases. Secondly, assuming a linear increase is the simplest assumption that does not overparameterize the model according to the experimental data. It is assumed that the contact area at the swallowing time A_{max} depends on the product and on the panellist. Formally, this can be written as the product of two functions:

$$A_{max} = F(\text{product}) \times G(\text{panellist}) \tag{1}$$

where F and G are two functions that depend on the product and on the panelist respectively

We observed experimentally that very few product remained in mouth after the first swallowing event t_s. Thus, the contact area and the product volume in the mouth are considered to be null.

2.5.2 Mathematical model formulation

The evolution of salt concentration in saliva C_s over time t is given by a mass balance between product and saliva and takes the dilution by the saliva flow rate Q_s into account (Figure 2-a). The salt concentration in the inlet saliva is referred to as C_Q:

$$V_s(t)\frac{dC_s}{dt} = k_p A(t)\left(K.C_p(t) - C_s(t)\right) + Q_s\left(C_Q(t) - C_s(t)\right) \tag{2}$$

where $K = C_s^{eq}/C_p^{eq}$ is the saliva/product partition coefficient and k_p the mass transfer coefficient (m/s). The remaining salt concentration in the product is:

$$V_p\frac{dC_p}{dt} = -k_p A(t)\left(K.C_p(t) - C_s(t)\right) \tag{3}$$

where V_p is the volume of product (m^3). As previously explained, the contact area is given by (Figure 2):

$$A(t) = \begin{cases} A_0 + (A_{max} - A_0)\,\frac{t}{t_s} \text{ if } t < t_s \\ 0 \text{ else} \end{cases} \tag{4}$$

where A_{max} is defined by (Eq. (1)).

Considering that saliva volume V_s decreases to its initial value at each swallowing (Figure 2), we have:

$$V_s(t) = \begin{cases} V_{s0} + Q_s t \text{ if } t < t_s \\ V_{s0} + Q_s\,(t - t_s) \text{ if } t_s < t < t_i \\ \ldots \end{cases} \tag{5}$$

where t_i ($i \in \overline{2..5}$) are the times of the different swallowing events (Figure 2)

The initial conditions are:

$$C_s(t=0) = C_Q \tag{6}$$

$$C_p(t=0) = C_{p0} \tag{7}$$

2.5.3 Inverse method for determining unknown model parameters

This equation system was solved with Matlab 7 (The Mathworks, Natick, MA, USA). Model parameters are summed up in Table 2. The value of K, k_p and C_{p0} were fixed and were those obtained by de Loubens et al. (*13*) for the same products. Partition coefficients K were comprised between 0.7 and 1, mass transfer coefficients k_p ranged between 2 and 3.10^{-6} m/s and initial salt concentration in the products C_{p0} were between 13 g/L and 17 g/L. Saliva flow rate Q_s was measured experimentally for each panelist. For each data set, salt concentration in inlet saliva C_Q was given by the concentration at the first point of the kinetics ($t=0$), which is the salt concentration in stimulated saliva. Three model parameters were unknown beforehand: the two functions F and G and the initial saliva volume V_{s0} which was assumed to be dependent on the panellist alone.

In a first step, fitting the model to all experimental data from the swallowing events (from $t=t_s$ to $t=t_5$) made it possible to determine the initial volume of saliva V_{s0} for each panellist. In fact, the concentration measured at the first swallow ($t=t_s$) is considered as an initial condition, the equation system is reduced to Eq. (2) and Eq. (5) where $A=0$ and is therefore independent of F and G.

In a second step, given V_{s0}, functions F(product) and G(panellist) were determined by fitting the model to the two first experimental points (from $t=0$ to $t=t_s$) for all data. Since F and G are defined up to a common multiplicative factor, it is necessary to fix the value of one of these functions for a panellist or a product. We initially set $F(250/40)=1$.

3 Results & Discussion

3.1 Impact of product on salty perception

The differences in perception of the studied dairy gels were previously highlighted by a profile method (*14*) and a temporal dominance of sensations method (*13*), which revealed, in particular, a strong effect of fat content and a weaker effect of dry matter content on salty perception, and a high product effect on the dynamics of dominance of salty and texture perception. Subsequent to this result, it seems important to study the dynamics of salty perception in order to identify and quantify the salt release mechanisms at the origin of perception using an experimental and modeling approach.

Figure 3 represents the time intensity profile averaged for each product and all panellists.A one-way ANOVA with product as factor was performed in order to analyse which time-intensity parameters that showed significant differences. The area under the curve (AUC) and the maximum intensity (Imax) were statistically influenced by the structure and composition of the products ($p<0.0001$). The maximum perceived intensity of the salty taste is significantly increased by fat addition for products with low dry matter. Moreover, when fat was present in the product, the maximum perceived intensity occured later, contrary to low-fat products.

3.2 Physiological parameters

The values of the physiological parameters used in the model are given Table 2. The experimental stimulated salivary flow rates Q_s were between 0.6 and 3.6 mL/min. The saliva volume V_{s0} obtained by fitting the model to the experimental data was between 0.3 and 2.5 mL. The salt concentration in stimulated saliva C_Q was approximately 1.3 g/L eq. NaCl. These data were in agreement with those in the literature (*3*, *21–23*).

3.3 Product and subject influences on salt release kinetics

Figure 4 shows typical evolutions of salt concentration in the mouth during the consumption of model dairy products for one panelist. For each piece of data, the associated error

bars show the minimum and maximum of the four replicates and are relatively small. Regardless of the product or the panelist, the kinetics had similar profiles. Between the time at which the product was put in the mouth and the first swallowing event, salt concentration increased due to the salt release from product to saliva. After the first swallowing event, the concentration decreased because the saliva remaining in the mouth was diluted by the saliva flow rate from the salivary glands, moreover the product was swallowed. The maximal concentrations of salt measured at the first swallowing event ranged from 8 to 13 g/L. This value can be compared to the initial salt concentration in the products that are between 15 and 17 g/L. Thus, at the first swallowing event, the solute distribution between the product and the saliva was relatively close to the equilibrium, implying that the maximal salt concentration could be reached at the first swallowing event.

Product and subject effects on salt release kinetics were tested statistically. Tests were performed on the following descriptors extracted from the release kinetics: (i) first swallowing time t_s, (ii) concentration at the first swallow $C_s(t_s)$ normalised by the initial concentration of solutes in the product C_{p0} and the partition coefficient K (i.e., $C_s(t_s)/KC_{p0}$) and (iii) characteristic time of the decreasing part of the kinetics τ (determined by fitting an exponential law on this part of the kinetics).

The first swallowing time ranged from 8 to 22 s. This parameter was influenced by product and subject, and a product-subject interaction was observed ($p < 10^{-4}$). The swallowing time was correlated with the breakdown energy E_b that describes mechanical properties of the product under large deformation ($R^2 = 0.95$, Figure 5).

The normalised concentration at the first swallowing time was influenced by product and subject, and a product-subject interaction was observed ($p < 10^{-4}$). The product 250/40 was significantly different from 150/40 (Table 3).

The characteristic time of the decreasing part of the kinetics τ provided information about the "salt persistence." The longer the τ is, the longer the solutes remain in the mouth and the more persistent the product is. As in the case of the other parameters, τ was influenced by the subject, the product and the product-subject interaction. Subject

influence could be mainly explained by the saliva volume and the salivary flow rate. Products were statistically classified into two groups (Table 3). The first group was composed of 250/40 only and the second one of 250/0, 150/0 and 150/40. Two hypotheses can be formulated to explain this phenomenon: either the saliva flow rate depended on the product or some little pieces of product adhered to the tongue surface and acted as a reservoir for solute release. Further studies are needed to improve our understanding of these phenomena.

In conclusion, product and subject influenced release kinetics and a product-subject interaction was observed. In the model, product influence was represented by the salt physico-chemical properties in the product (mass transfer coefficient k_p and partition coefficient K) and subject influence was represented by its physiological parameters (the initial saliva volume and the salivary flow rate). The product / subject interaction was introduced by considering that the maximal contact surface during the mastication A_{max} was a function of both the product and the panellist. We assumed that the initial volume of saliva V_{s0} and the salivary flow rate Q_s were product- and time- independent.

3.4 Modeling salt relase during food consumption

Model sensitivity analysis

In this section, the effects of some of the parameters on model predictions are analysed. The values used for the sensitivity analysis were chosen according to the physiological values measured in this study and the physico-chemical parameters measured by de Loubens et al. (*13*). As shown in Figure 6-a, the product/saliva contact area A_{max} mainly has an influence on release kinetics before the first swallowing event. The greater the contact area is, the faster the solute release is. When the area is sufficiently large, the salt equilibrium between the saliva and the product is reached before the first swallowing event.

The initial volume of saliva V_{s0} has an influence on the salt concentration at the first swallowing event and on the decay of salt concentration after this event (Figure 6-b). A small saliva volume induces a high salt concentration in saliva, but the decay of the

concentration after the first swallowing event is faster. Since the characteristic time of the decay is given by the ratio V_{s0}/Q_s, a large saliva volume and a weak saliva flow rate increase the "salt persistence" of the product.

A high saliva flow rate Q_s reduces the salt concentration at the first swallowing event and accelerates the decay by diluting salt in saliva (Figure 6-c).

Relationship between the maximal contact area A_{max}, the product and the subject

In Section 2.5, the maximal product / saliva contact area A_{max} was assumed to be the product of two functions F and G that depend only on the product and the panellist respectively: $A_{max} = F(\text{product}) \times G(\text{panellist})$. This equation allowed us to determine the respective contribution of the product and of the panellist to the dynamics of contact area generation.

After fitting the model to the salt release kinetics as explained in Section 2.5, a good regression between the function G and the masticatory performance M_sP was found ($R^2 = 0.90$ Figure 7):

$$G = \alpha \exp(\beta \times M_sP) \tag{8}$$

where α and β are two constants. Finally, A_{max} is reduced to a function of F ($F \leftarrow \alpha F$) and M_sP:

$$A_{max} = F(\text{product}) \exp(\beta \times M_sP) \tag{9}$$

Considering that A_{max} is given by Eq. (2), the values of F, β and V_{s0} previously obtained were used as an initial attempt to fit the model to the complete kinetics (from $t = 0$ to $t = t_5$, Figure 2) in order to refine the values of F, β and V_{s0}. The determination coefficient R^2 was 0.91. We determined that $\beta = 3.9 \pm 0.2$ and V_{s0} was between 0.3 and 2.5 mL.

In Figure 8, we can observe that the values of F between each product were close

compared to the inter-individual variability (Function G). We compared the value of F with the area generated by a standardised compression under *in vitro* conditions A_c, which was determined by de Loubens et al. (*13*) (Figure 8). This parameter (A_c) is a representation of the breakdown product properties translated in terms of contact area of the product with the surrounding aqueous phase. The product 250/40 had a value of F that was slightly higher than the others products. This difference was more evident after the *in vitro* compression. In fact, panellists adpat their mastication behaviour according to the product structure (Figure 5): the firmer the product is, the longer the subject chews it before swallowing and the greater the quantity of salt released is. Similar results have already been observed (*24–27*). Depending on their texture perception, subjects adapted their chewing time to reach the same bolus state. The analysis of the ready-to-swallow bolus by image analysis revealed similar results (*19*): mean particle width and particle size distribution do not depend on the specific food (ex: carrot and radish) but, instead, on the food type (ex: dried nuts and raw vegetables).

Finally, A_{max} is clearly related to the subject's masticatory performance and is slightly dependent on the breakdown properties of the product.

However, as shown in Figure 9, the dynamics of contact area evolution (represented by the ratio $F(product)/t_s$) is very different between the products. $F(product)/t_s$ is very well correlated with the fracture initiation energy E_{fi} ($R^2 = 0.94$). $F(product)/t_s$ represents the dynamics of evolution of the contact area between the product and the saliva independently of the panelist effect.

Final model adjustment

Figure 10 shows the salt release kinetics fitted to the experimental data (from A_{max} defined with Eq. (9)) for two panelists (subjects 4 and 7) and two products varying in fat content (250/40 and 250/0). The comparison of these two panellists is interesting since they had different physiological parameters and different behaviours. In fact their masticatory performance M_sP was very different: 0.52 (subject 4) and 0.19 (subject 7). For panelist 4, the maximal contact area A_{max} generated with product 250/40 was

sufficiently large (281 cm^2) so as not to limit salt release (Figure 10): the concentrations of salt between the product and the saliva were very close to the equilibrium at the first swallowing event. In contrast, panellist 7's masticatory behaviour did not make it possible to generate a sufficiently large area, regardless of the product ($A_{max} < 75$ cm^2, Figure 10-b): the saliva/product equilibrium was never reached at the first swallowing event. The panellist's masticatory performance therefore limited the generation of contact area and salt release. Compared to the inter-individual variability, the differences between the products were relatively low. However, a greater maximal contact area was generated with the fat product (250/40) than with the non-fat product. These differences can be explained by a longer mastication time for fat products that are related to the breakdown energy (Figure 5) and by the different breakdown properties between the two products (Figure 8, Figure 9).

Finally, considering that salt release can be described by a mass transfer coefficient and that salt concentration in the bulk product remains homogeneous during the small residence time of the product in the mouth, this simplifies the formulation of the mathematical problem and reduces the number of parameters to be known. These hypotheses have already been successfully validated on *in vitro* data by de Loubens et al. (*13*). In fact, only the product volume and the saliva/product contact area need to be known. The evolution of the contact area was assumed to be linear. It could be refined and improved if more detailed experimental data were available, namely during the first seconds of the mastication period. New experimental methodologies must be developed to acquire such data without disturbing the natural mastication behaviour of the panellists.

Salty perception and salt release kinetics

No direct relationships were observed between the salt release kinetics and the salty intensity of the time-intensity profiles on the basis of data from the present study. For example, the correlation coefficient between the area under the curves of the time-intensity profile and the concentration reached at the first swallowing event is 0.2. Morris et al. (*28*) suggested that the overall amount of delivered salt affects sensory perception. In

the present study, the quantity of salt delivered during mastication was calculated using the mechanistic model. The relationships between this parameter and the area under the curves of time-intensity profiles and the maximal intensity are not satisfactory ($R^2 < 0.1$).

However, specific studies on sensory receptors assume that receptor response depends on the type of stimulation: the rate of taste molecules transported to the taste receptors can influence the receptor response (*29–31*). Busch et al. (*32*) investigated this hypothesis for salt perception on humans. On the basis of salt pulse experiments, they concluded that the frequency, timing and concentration differences of salt stimuli can affect saltiness. For aroma compounds, Baek et al. (*33*) showed no correlation between the amount of volatile release and the sensory analysis, but found a good correlation between the rates of volatile release and the sensory data. In order to investigate the hypothesis that perception is related to the salt release rate, we simulated the salt release rate with the model developed and the parameters determined in the present study and calculated the maximal slope of the evolution of salt concentration in saliva (i.e., $\max(dC_s/dt)$). A better correlation between the maximal salty intensity and the maximal slope of the evolution of salt concentration ($R^2 = 0.6$) was observed. This result suggests that salt perception can be partly explained by the rate of salt release. However, this relationship between release and perception needs to be investigated further. Controlled salt delivery experiments should allow us to determine the links or the "transfer function" between release and perception.

To conclude, the model developed in the present study made it possible to better understand the mechanisms of salt release and perception during food consumption with physiological parameters (salivary flow rate and masticatory efficiency) and the rheological and breakdown parameters of food. This type of model could be a good tool to formulate products that satisfy both nutritional and organoleptic criteria.

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List of Tables

Table 1: Composition and codes of model dairy products.

	250/40	250/0	150/40	150/0
Milk retentate powder [g/kg]	250	250	150	150
Anhydrous milk fat [g/100g DM]	40	0	40	0
Water [g/kg]	573	740	740	850

Table 2: Model parameters: mean values and standard deviation (SD)

Model parameters	**Unit**	**Symbol**	**Mean±SD**	**References**
Saliva flow rate	[mL/min]	Q_s	2.2±0.9	1.7±0.6 (*3*)
				1.2±0.8 (*21*)
				1.5±0.5 (*22*)
Volume of saliva	[mL]	V_{s0}	1.1±0.6	0.7±0.3 (*23*)
Salt concentration in stimulated saliva	[g/L eq. NaCl]	C_Q	1.3±0.6	2.5±1.2 (*3*)
Salt partition coefficient product / saliva	[-]	K	0.85±0.15	0.75±0.15 (*27*)
Mass tranfer coefficient	[x10^{-6}m/s]	k_p	2.2±0.3	

Table 3: Normalized concentration $C_s(t_s)/KC_{m0}$ at the first swallowing and mean characteristic time τ of the decreasing part of release kinetics for the different products with confidence intervals. The products are statistically classified in two groups referred to as a and b (SNK Test).

	Normalized concentration $C_s(t_s)/KC_{m0}$ [-]	Characteristic time of the decay τ [s]
250/40	0.77±0.04 (a)	56±14 (a)
250/0	0.71±0.04 (a,b)	45±11 (b)
150/40	0.63±0.03 (b)	43±8 (b)
150/0	0.70±0.05 (a,b)	45±12 (b)

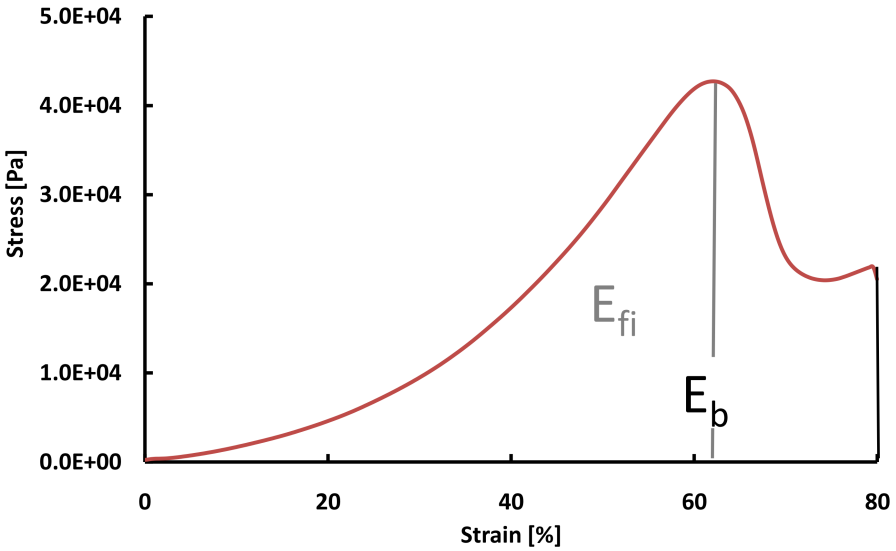

Figure 1: Typical stress-strain curve during product compression. The maximum of the curve represents fracture initiation. Breakdown energy E_b is defined as being the energy necessary to break up the product at 80% of strain (i.e total area under the curve). Fracture initiation energy E_{fi} is defined as being the energy necessary to initiate the fracture in the product. These data were calculated from the experiments carried out in (*14*).

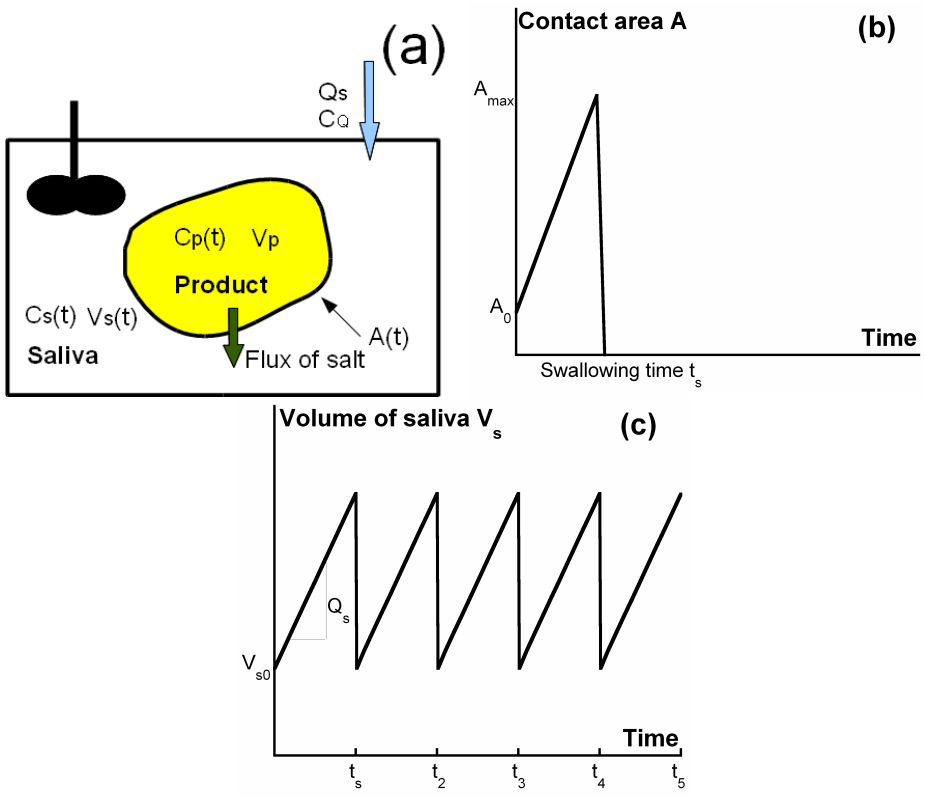

Figure 2: Model assumptions: (a) principles and notations of the in-mouth salt release model during eating; (b) hypothesis of the change of the contact area between the product and the saliva during eating; (c) hypothesis of evolution of saliva volume in mouth during eating.

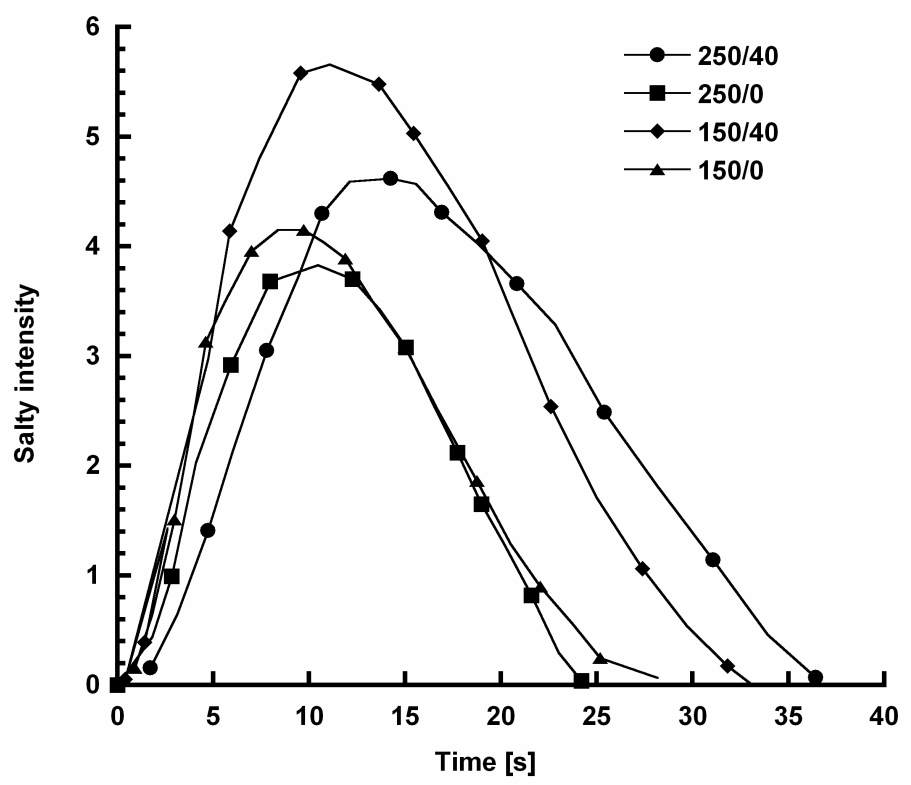

Figure 3: Mean of the time-intensity profiles for the four dairy gels.

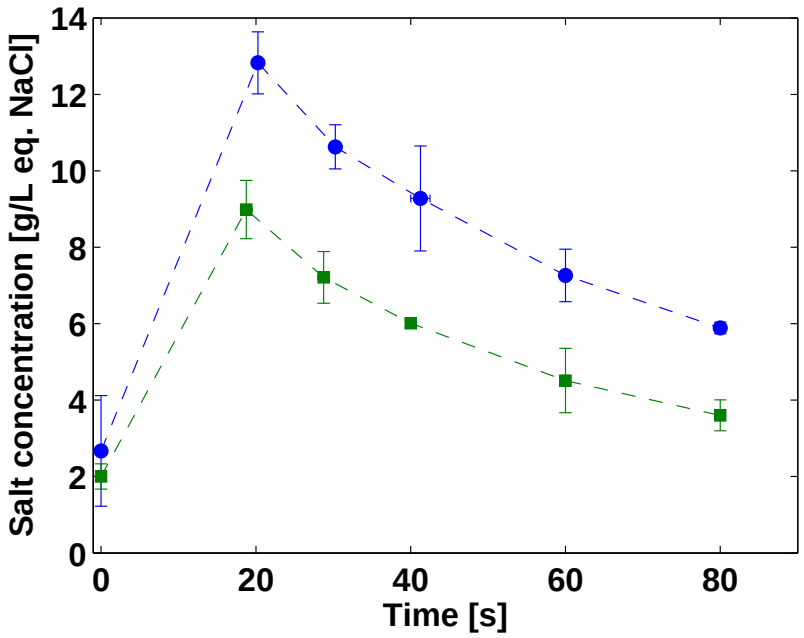

Figure 4: Examples of experimental release kinetics of salt in saliva for a panelist and two products: 250/40 (-●-), 250/0 (-■-).

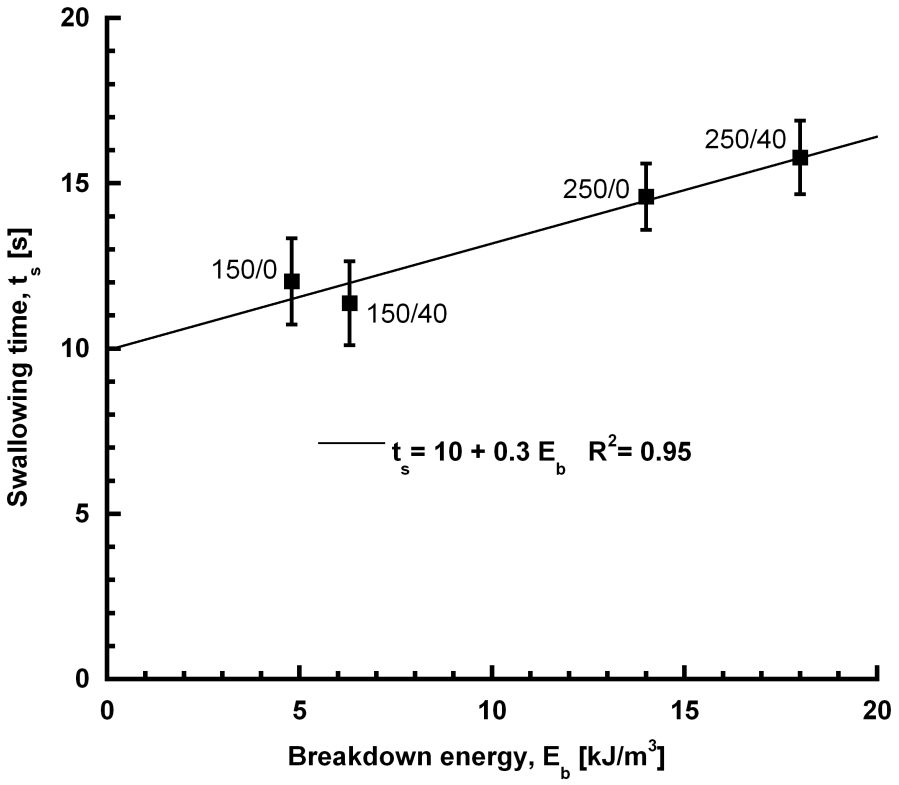

Figure 5: Mean swallowing time t_s as a function of the breakdown energy E_b for each product. Breakdown energy E_b is defined as the energy necessary to break up the product at 80% of strain during a compression test (data calculated from the experiments carried out in (*14*)). Error bars represent confidence intervals.

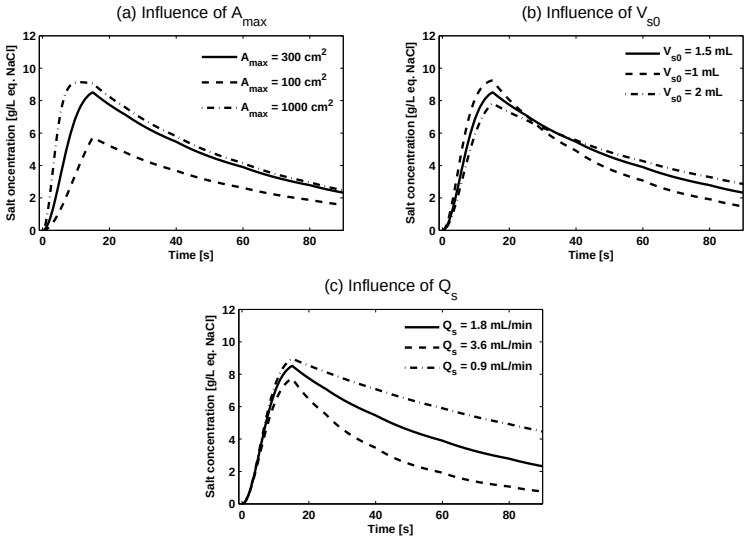

Figure 6: Parameter influence on model predictions: influence of the maximal contact area A_{max} (a); influence of the initial volume of saliva in the mouth V_{s0} (b); influence of the saliva flow rate Q_s (c). The swallowing events take place at 15, 25, 40, 60 and 80 s. Unless otherwise specified, parameter values are: $A_{max} = 100\,cm^2$, $V_{s0} = 1\,mL$ $Q_s = 1.8\,mL/min$, $K = 0.8$, $k_p = 2.10^{-6}\,m/s$, $V_p = 5\,mL$.

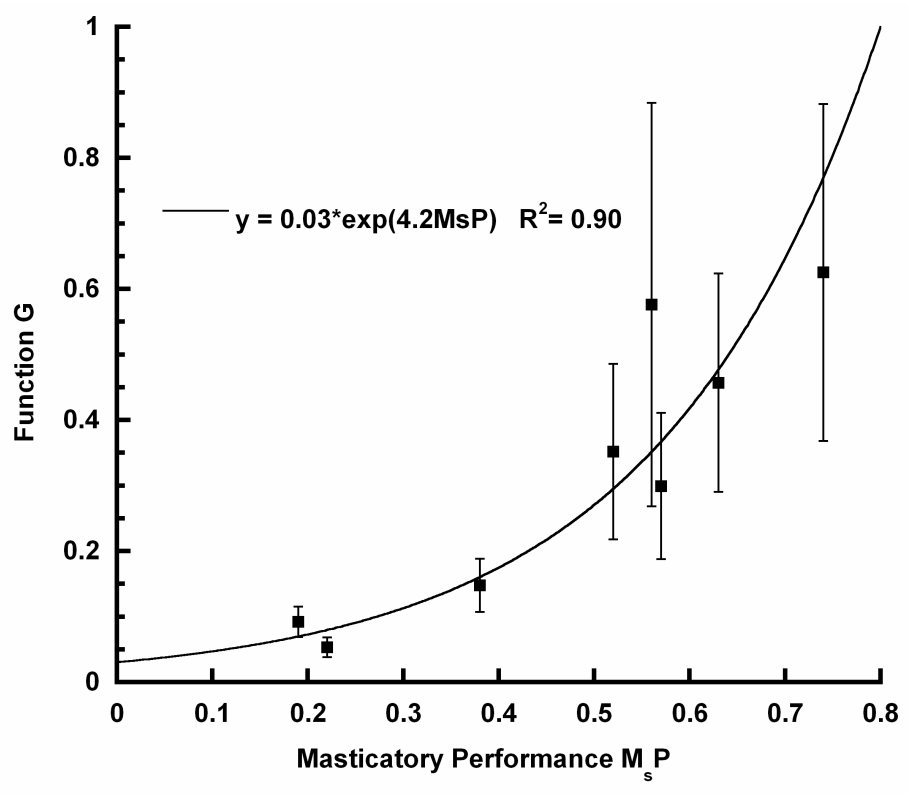

Figure 7: G as a function of the masticatory performance. Each point represents a panelist. Error bars represent confidence intervals.

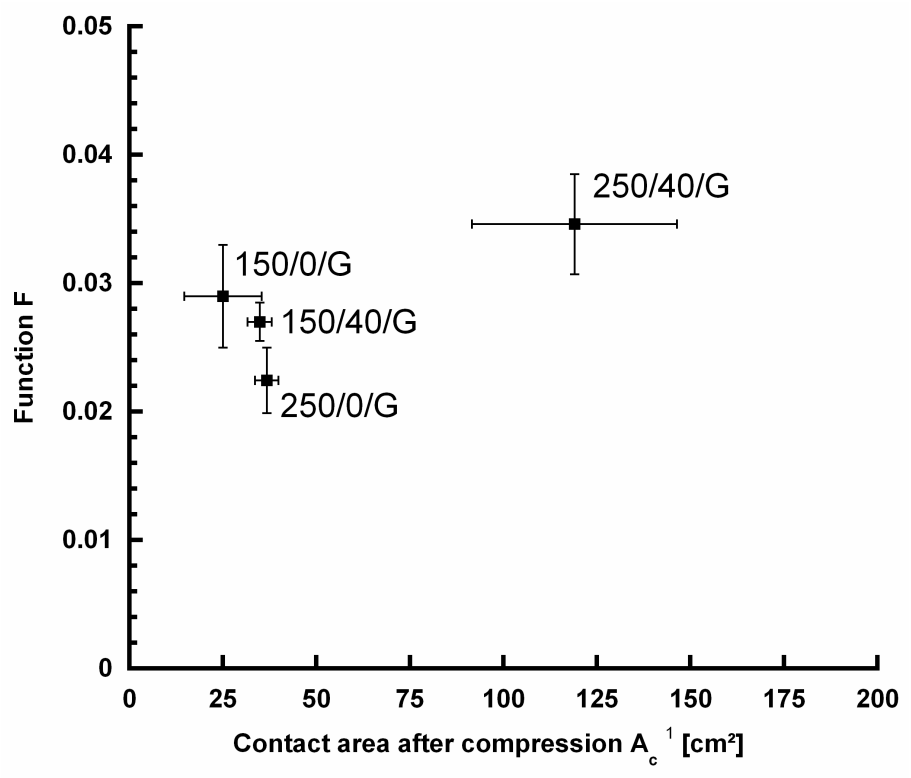

Figure 8: F as a function of the contact area obtained after a standardised compression A_c (^{1} data from (*13*).). Error bars represent confidence intervals.

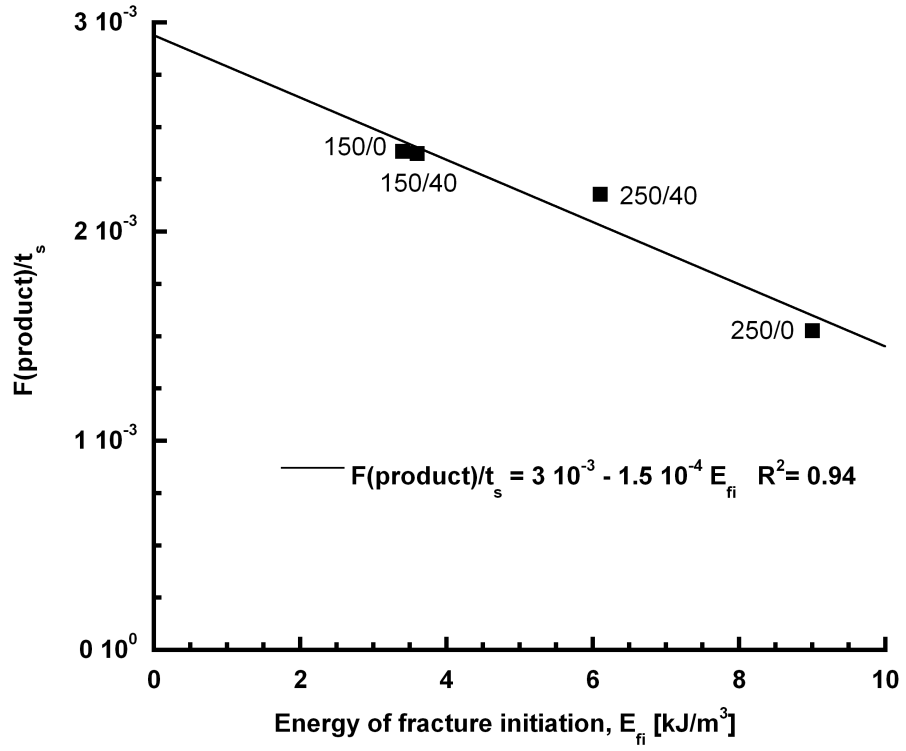

Figure 9: $F(product)/t_s$ as a function of the fracture initiation energy E_{fi}. $F(product)/t_s$ represents the dynamics of evolution of the contact area between the product and the saliva independently of the panelist effect. Fracture initiation energy E_{fi} is defined as being the energy necessary to initiate the fracture in the product during a compression test (data calculated from the experiments carried out in (*14*)).

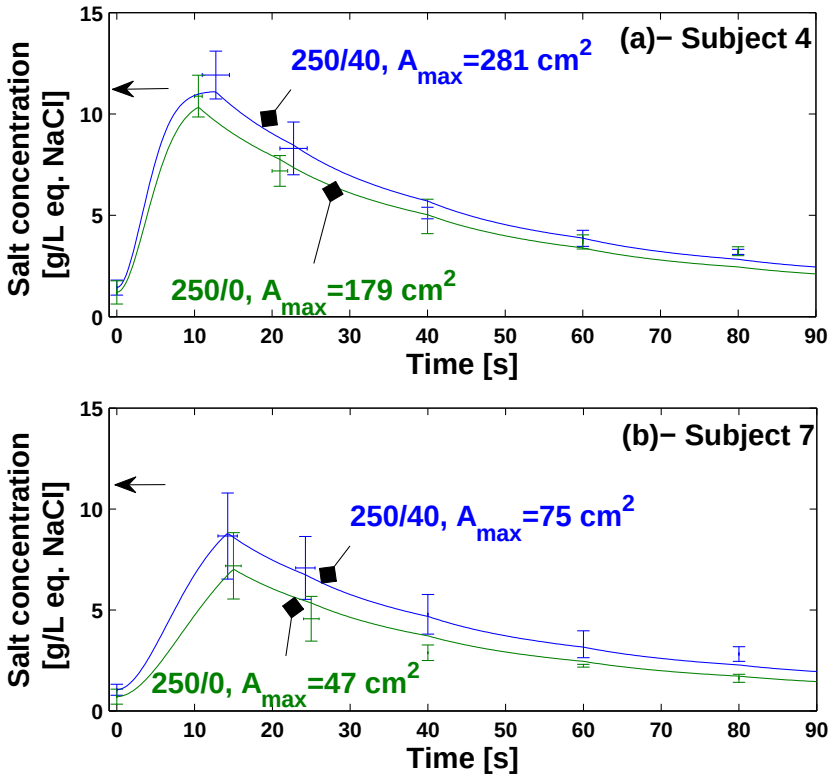

Figure 10: Experimental data and model of solutes release for two panelists with different masticatory performances ($MsP = 0.52$ (a), $MsP = 0.17$ (b)) and two products (250/40 and 250/0). Arrows indicate the equilibrium salt concentration in saliva at the first swallowing event.