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Oral Shear Stress Predicts Flavour Perception in Viscous Solutions

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Abstract

The perception of sweetness and flavour were studied in viscous solutions containing 50 g/l sucrose, 100 p.p.m. iso-amyl acetate and varying concentrations of three hydrocolloid thickeners (guar gum, λ-carrageenan and hydroxypropylmethyl cellulose). Zero-shear viscosity of the samples ranged from 1 to 5000 mPas. Perception of both sweetness and aroma was suppressed at thickener concentrations above c^* (coil overlap concentration, the point at which there is an abrupt increase in solution viscosity as thickener concentration is increased). Sensory data for the three hydrocolloids was only loosely correlated with their concentration relative to c^* (c/c^* ratio), particularly above c^*. However, when perceptual data were plotted against the Kokini oral shear stress (τ), calculated from rheological measurements, data for the three hydrocolloids aligned to form a master-curve, enabling the prediction of flavour intensity in such systems. The fact that oral shear stress can be used to model sweetness and aroma perception supports the hypothesis that somatosensory tactile stimuli can interact with taste and aroma signals to modulate their perception.

Key words: flavour intensity, hydrocolloid thickener, oral shear stress, sensory perception, viscosity

Introduction

Increasing the viscosity of liquid foods with hydrocolloid thickeners is known to change the sensory properties of such systems. Both taste and aroma perception can be suppressed by increasing concentrations of hydrocolloid, although effects are specific to the taste-modality, flavouring and hydrocolloid concerned (Pangborn *et al*., 1973; Pangborn and Szczesniak, 1974). With sweetness perception, however, the effect appears to be more generic. Investigators have reported a decrease in perceived sweetness intensity in solutions thickened with a range of hydrocolloids (Vaisey *et al*., 1969; Moskowitz and Arabie, 1970; Christensen, 1980; Paulus and Haas, 1980; Izutsu *et al*., 1981; Baines and Morris, 1987; Malkki *et al*., 1993). This effect has been observed for both sugars and high-intensity sweeteners of wide-ranging chemical nature and different modes of taste chemoreception (Cook *et al*., 2002).

Baines and Morris (Baines and Morris, 1987) investigated both sweetness and strawberry flavour perception in solutions thickened with guar gum. They concluded that the key determinant of flavour suppression in such systems was the thickener concentration relative to its coil-overlap concentration (c^*). This is the point at which there is an abrupt increase in solution viscosity as thickener concentration is increased. At a molecular level, this phenomenon is interpreted as the point at which the hydrocolloid chains begin to overlap in solution, reducing freedom of molecular movement and resulting in a sharp increase in viscosity. At concentrations below c^*, Baines and Morris found that sweetness and strawberry aroma perception were relatively unchanged, whilst both were progressively suppressed at thickener concentrations above c^*. A theory was developed to model flavour perception in a range of hydrocolloid matrices in terms of thickener concentration relative to c^* (Baines and Morris, 1988). Baines and Morris proposed that perceptual changes might be linked to inefficient mixing in solutions above c^*, inhibiting the transport of small taste and aroma molecules to their respective receptors. Hollowood *et al*. (Hollowood *et al*., 2002) used real-time analysis of in-nose volatile release by atmospheric pressure ionization mass spectrometry (API-MS) (Taylor *et al*., 2000) to show that retronasal benzaldehyde release was not substantially changed by hydroxypropylmethyl cellulose (HPMC) at up to 2.1 times the c^* concentration. Perception of almond flavour was nonetheless shown to decline sharply above c^*, in accordance with the results of Baines and Morris. Similar findings were reported for ethyl butyrate and strawberry flavour perception at up to $3.5c^*$ HPMC concentration. These results were explained in terms of a taste–aroma interaction (Noble, 1996; Davidson *et al*., 1999), with the perceived drop in sweetness of the system

driving the decline in perceived aroma, even though the concentration of aroma compound reaching the olfactory receptors remained broadly constant. The key question then concerns the mechanism behind the drop in perceived sweetness in such systems.

When foods are consumed, perceived flavour is a result of the simultaneous stimulation of three principal sensory systems (Cerf-Ducastel and Murphy, 2001): taste, olfaction and the trigeminal system. The latter comprises chemical, thermal and tactile stimulation of the somatosensory system. One such tactile stimulus, oral viscosity, is perceived by mechano-receptors in the mouth and in particular on the tip of the tongue (Guinard and Mazzucchelli, 1996). Whilst taste–aroma interactions have been well studied and are widely accepted, potential interactions between somatosensory information and taste or olfaction have received less attention. The current study investigated the relationship between oral viscosity and the perception of sweetness and aroma in hydrocolloid systems.

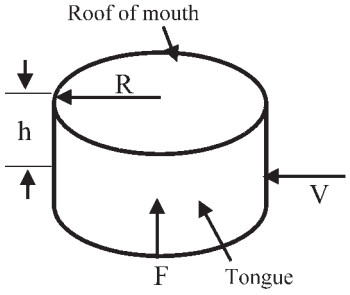
Many workers have studied the oral perception of viscosity, yet few have looked at the way that this interacts with food flavour. Two groups (Cussler *et al*., 1979; Kokini *et al*., 1982) investigated the effects of increasing viscosity on taste perception. However, in each case, the focus was on predicting how changes in viscosity would affect diffusion rates in the hydrocolloid matrix, thus reducing the flux of taste molecules to the tongue's surface. Cussler *et al.* (Cussler *et al.*, 1979) reported some success in fitting sensory data by this method; however, their diffusion coefficients were predicted theoretically from high-shear viscosity measurements and not determined experimentally. They also found that consideration of diffusion factors alone failed to predict the perception of several taste compounds in thickened solution, in which cases they assumed mass transfer to be non rate-limiting. However, there was no clear rationale behind which compounds/tastes could be modelled in this fashion and which could not.

Hydrocolloid solutions are non-Newtonian in nature, which means that they have different apparent viscosities (the ratio of shear stress to shear rate) dependent on the shear stress applied. Because of this, the apparent viscosity of such solutions is normally quoted together with the measured shear rate (the velocity gradient set up in a solution under applied stress). Hydrocolloids are typically shear-thinning in nature, meaning that as the applied shear stress is increased, the apparent viscosity decreases. The zero-shear viscosity, normally extrapolated from experimental data, is the viscosity as the shear rate tends to zero, and is therefore the highest apparent viscosity for shear-thinning fluids.

The sensory thickness, or oral viscosity, of shear-thinning hydrocolloids thus depends on the shear stress applied to the fluid in-mouth and the resultant shear rate. Wood (Wood, 1968) correlated the perceived texture of hydrocolloids with their rheological flow properties and concluded that the stimulus associated with the oral evaluation of viscosity was a shear stress developed in mouth at a constant shear rate of ~50 s^{-1}. Shama and Sherman (Shama and Sherman, 1973) looked at the perception of viscosity in a range of fluid and semi-solid foods. They concluded that a much wider range of shear rates were operative in-mouth (10–1000 s^{-1}), dependent on the flow characteristics of the food. The stimulus associated with the evaluation of fluid foods appeared to be the shear rate developed at a constant shear stress of ~10 Pa; for highly viscous foods, the stimulus was reported to be the shear stress developed at a constant shear rate of ~10 s^{-1}. Between these extremes, there was a curved space defining the limits of oral viscosity evaluation within the shear stress–shear rate plane. Richardson *et al.* (Richardson *et al.*, 1989) continued attempts to correlate sensory perception of thickness with rheological measurements. They reported that small deformation measurements of dynamic viscosity (η^*) under oscillatory shear at ~ 50 rad/s correlated directly with the perceived thickness of both true solutions and weak gels. However, there was no clear underlying mechanism for this correlation, and the authors concluded that the relevant sensory stimulus was probably a related 'large-deformation' property, such as the peak shear stress developed in moving the sample from rest.

Jozef Kokini and co-workers used fluid dynamics to calculate theoretically the shear-stress on the tip of the tongue resulting from the manipulation of fluid samples in-mouth. This approach was developed in a series of publications (Kokini *et al.*, 1977; Kokini and Cussler, 1983; Kokini, 1985). The calculation assumes a 'parallel-plate' model (Figure 1), with a cylindrical plug of fluid between the tongue and roof of the mouth. The two plates are slowly squeezed towards one another by a normal force W; simultaneously, the two plates move steadily relative to one another at velocity V. Calculation of the resultant shear stress was solved mathematically (deMartine and Cussler, 1975), leading to equation (1) (Figure 1). Kokini made what he decided were reasonable assumptions for the forces, dimensions and velocities involved (Figure 1), and held these to be relatively constant for all samples. Under these conditions, the principal variables in the equation predicting oral shear stress are m and n, the power law constants for the fluid concerned. Elejalde and Kokini (Elejalde and Kokini, 1992) applied this technique for predicting oral shear stresses to the evaluation of a range of hydrocolloid solutions and real fluid foods. They were able to show that sensory perception of thickness can be predicted by the Kokini oral shear stress, based on simple rheological measurements. In addition, they concluded that the shear stress in mouth is in fact the sensory mechanism used for the oral evaluation of viscosity, since the exponent of the psychophysical law relating sensory viscosity to shear stress was close to 1. They were able to use this approach to model sets of data published by other research groups.

Until now, no one had taken the further step of demon-



V = velocity of tongue (2 cms^{-1})
F = Normal force (1 N)
R = radius of plug (2.5 cm)
t = time (1s)
h_0 = initial plug height (0.2cm)
m = consistency index
n = power law index

(values in brackets are those assumed in the calculation of oral shear stress)

$$\tau = mV^n \left[\frac{1}{h_0^{(n+1)/n}} + \left(\frac{F}{R^{n+3}} \cdot \frac{n+3}{2\pi m} \right)^{1/n} \cdot \frac{(n+1)t}{2n+1} \right]^{n^2/(n+1)} \quad (1)$$

Figure 1. A model mouth geometry: the Kokini model for predicting oral shear stress.

strating a link between oral shear stress and the overall perception of flavour, as proposed in this paper.

Materials and methods

Stimuli

Solutions were flavoured with 50 g/l sucrose and 100 p.p.m. iso-amyl acetate, and contained one of eight concentrations of each thickener used in the study (HPMC, guar gum or λ-carrageenan; 24 samples in total). Thickener concentrations were calculated relative to their c^* values, and were 0 (i.e. water), $c^*/4$, $3c^*/4$, c^*, $5c^*/4$, $7c^*/4$, $10c^*/4$ and $14c^*/4$. Measurement of c^* for these samples has been described previously (Cook *et al.*, 2002). Resultant values were 5.7 g/l (HPMC), 1.9 g/l (guar gum) and 4.8 g/l (λ-carrageenan). The experimental design was weighted around c^* to focus on perceptual changes in this region, but included a wide range of viscous stimuli, from 1 mPas (water) to ~5 Pas zero-shear viscosity (η_0) for the most viscous samples.

Hydrocolloids were dispersed in water using an overhead paddle stirrer at 200–600 r.p.m. Guar gum (purified grade; SKW Biosystems, La Ferté-sous-fociaire, France) was dispersed in water at room temperature, HPMC (Methocel, The Dow Chemical Company, Langhorne, PA) at 95°C and λ-carrageenan (Red Carnation Gums Ltd, Basildon, Essex, UK) at 60°C. All three hydrocolloid dispersions were subsequently cooled to 5°C and stirred for a further 6 h to ensure adequate hydration of polymer chains. Samples for sensory analysis were prepared by weighing appropriate quantities of hydrocolloid, water and sucrose into sample bottles and mixing thoroughly on a roller bed (SRT2; Stuart Scientific, Redhill, UK). A flavour concentrate of iso-amyl acetate (230 µl) in food-grade absolute ethanol with yellow food colouring (total volume 10 ml) was prepared and added to each solution at a rate of 0.5 ml per 100 ml to yield a final concentration of 100 p.p.m. iso-amyl acetate. Flavoured solutions were then rolled for a further 2 h, to ensure adequate mixing, prior to presentation for sensory analysis. The yellow colouring acted as a check on adequate mixing of the solutions and also masked some of the visual differences between samples (e.g. degree of clarity).

Sample rheology

The flow characteristics of each solution were measured at 25°C on a Bohlin CS-10 applied stress rheometer (Bohlin Instruments, Lund, Sweden). Double-gap geometry was used for the less-viscous solutions, and cone and plate geometry for samples with zero-shear viscosities of >600 mPas. The resultant shear rate range was between 1 and 100 s^{-1}. Measurements were performed in duplicate on the same batch of solutions prepared for sensory analysis. Flow curves were fitted to the Cross equation (Cross, 1965) using CS-10 software, to enable calculation of the apparent viscosity at any shear rate in the range and extrapolation to the zero-shear viscosity (*y*-axis intercept). The power law region of each flow curve was fitted to equation (2) in order to estimate the power law parameters of the samples.

$$\eta = m\gamma^{n-1} \quad (2)$$

where η is the apparent viscosity, γ is the shear rate, m is the consistency index and n is the power law index.

API-MS analysis of volatile release from samples

Real-time in-nose release of iso-amyl acetate during consumption of the samples was measured using the MS-Nose™ (Micromass, Manchester, UK). Five panellists consumed two replicates of each hydrocolloid solution, according to a fixed protocol. They were asked to breathe in, sip 8 ml of solution from a spoon, close their mouth and swallow the sample, then exhale and continue to breathe normally whilst resting their nose on the MS-Nose™ nasal sampling tube. Air from the nose was sampled directly to the source of an API-MS at 30 ml/min (Taylor *et al.*, 2000) and the release of iso-amyl acetate followed by monitoring m/z 131 (the mass to charge ratio for the molecular ion). The in-nose concentration of iso-amyl acetate was calculated by comparison with the signal for a calibrant of known concentration (Taylor *et al.*, 2000).

Subjects

An established and trained panel of 15 assessors (5 male, 10 female) aged between 30 and 55 years, was used in the study. The panel had been recruited and selected on the basis of their sensory acuity, in particular their ability to distinguish between concentrations of the same stimulus. They received specific training in the use of magnitude estimation against a fixed modulus and had >2 years of experience in conducting such tasks [see, for example (Hollowood *et al.*, 2002)].

Sensory analysis

Magnitude estimation against a fixed modulus was used to appraise the sweetness and flavour intensities of the solutions. The aqueous sample was used as the reference, and was assigned a score of 100 for both sweetness and iso-amyl acetate ('banana'/'pear-drop') flavour. Panelists were instructed to assign a score to each sample in turn, to represent the perceived intensity of a particular sensory attribute relative to the reference (= 100). To minimize the potential for halo-dumping effects, the panel were advised that they would have the opportunity to score the same samples for both sweetness and flavour in separate sessions, but to focus solely on the sensory attribute being scored in that particular session. Solutions were presented in groups of four for appraisal against a fresh reference sample. Presentation was ordered by a randomized complete block design and each panelist scored the reference as a sample twice in every panel session. The 24 samples were scored in duplicate for both sweetness and flavour (three panel sessions for each attribute).

Samples were presented in coded plastic cups and evaluations conducted in isolated booths under controlled lighting conditions. Solutions were tasted from a spoon (8 ml). Plain crackers and water were supplied to assist in cleansing the palate between tastings.

Sensory data analysis

The mean magnitude estimation scores from 10 sets of sensory data were selected for modelling. The criterion for inclusion was that the panelists' mean score for the reference when presented as a sample was 100 ± 25%. Consistency of scores when presented with replicates of the same sample was also taken into account when further selecting the 10 best sets of sensory data for modelling.

Mean sensory data was plotted in a conventional psychophysics log–log format against c/c^* and measured rheological properties of the solutions [consistency index, oral shear stress (τ) and the apparent viscosity at shear rates of 0, 50 and 100 s^{-1}]. These plots were fitted with two linear regressions, corresponding to below c^* and above c^* series.

Design Expert 6.0.2 software (Statease, Minneapolis, MN) was used to model the mean sensory data and to perform an analysis of variance (ANOVA).

Model validation experiment

Models for sensory perception, developed to fit the initial data set, were tested in a subsequent experiment using xanthan (1, 4 and 7.5 g/l) and methyl cellulose (4 and 8 g/l) thickeners, as well as different concentrations of HPMC ($12c^*/4$) and guar gum ($18c^*/4$). These were chosen to

Table 1 Rheological properties of the hydrocolloid solutions

Thickener	Conc.	Zero-shear viscosity (mPas)	Consistency index '*m*' ($mPas^n$)	Power law index '*n*'	Kokini oral shear stress (Pa)
Water	–	1.0	1.00	1.00	0.66
Guar	$c^*/4$	2.7	2.43	1.00	1.02
	$3c^*/4$	10.7	13.8	0.89	1.87
	c^*	22.0	34.0	0.81	2.48
	$5c^*/4$	41.5	82.3	0.72	3.13
	$7c^*/4$	136	247	0.64	4.91
	$10c^*/4$	863	1340	0.47	9.29
	$14c^*/4$	3578	3790	0.37	14.9
HPMC	$c^*/4$	3.9	3.04	0.98	1.08
	$3c^*/4$	16.8	18.4	0.96	2.57
	c^*	33.1	41.4	0.93	3.65
	$5c^*/4$	71.6	91.2	0.89	5.11
	$7c^*/4$	214	357	0.80	8.84
	$10c^*/4$	1111	1710	0.71	18.5
	$14c^*/4$	4664	10 600	0.52	43.3
λ-Carrageenan	$c^*/4$	5.5	6.06	0.95	1.44
	$3c^*/4$	31.5	47.7	0.83	3.09
	c^*	55.2	93.1	0.77	3.88
	$5c^*/4$	86.6	170	0.72	4.76
	$7c^*/4$	212	353	0.69	6.90
	$10c^*/4$	752	1430	0.53	11.2
	$14c^*/4$	3915	4040	0.45	18.9

present a range of viscous stimuli across the breadth of the original model.

Xanthan gum (food grade; Red Carnation Gums Ltd) was dispersed at room temperature and methyl cellulose (The Dow Chemical Company) at 60°C. All other details of solution preparation were as described above.

Sensory and rheological testing was conducted as described previously. To calculate apparent viscosities at a range of shear rates for xanthan samples, the power law (equation 2) was used to fit flow curves, as these could not be adequately fitted with the Cross equation.

Results

Sample rheology

Rheological data for the samples are detailed in Table 1 (mean of two replicate analyses). Values for the Kokini oral shear stress (τ) of each sample were calculated from the power law parameters fitted to each flow curve, and using the equation and assumptions shown in Figure 1.

API-MS analysis of volatile release from samples

API-MS analysis showed that the in-nose release of iso-amyl acetate from samples was relatively independent of thickener concentration (Figure 2). The pooled area data for the first three exhalations after swallowing reflect the total amount of volatile release from the sample (>99%), since iso-amyl acetate is not persistent on the breath (Linforth and Taylor, 2000). The first exhalation peak concentration is indicative of the maximum stimulus reaching the olfactory receptors.

Thus, neither the maximum concentration nor the total amount of iso-amyl acetate reaching the olfactory receptors was substantially affected by thickener type or concentration.

Sensory analysis

The perception of both sweetness and iso-amyl acetate flavour was suppressed by increasing concentrations of each of the three hydrocolloid thickeners (Table 2).

Mean sensory data for flavour and sweetness perception were plotted on a log–log scale against c/c^* (Figure 3). There were small reductions in mean sensory scores at thickener concentrations below c^*, with sweetness and flavour suppression increasing sharply above the c^* concentration. Whilst the data could be fitted with a polynomial function, it was felt that results were best portrayed by two straight lines, intersecting in the region of c^*, since it is difficult to propose a mechanism that would result in a curve on a double logarithmic plot. The plots were fitted with two linear regressions, corresponding to the below c^* and above c^* series, and an R^2 value was calculated for the fit to the Boolean function thus formed. This process was repeated for plots of the sensory data against a range of measured rheological properties of the solutions, in place of the c/c^* ratio. Table 3 shows the resultant fit between these rheological parameters and the sensory data. The Kokini oral shear stress was the factor which showed the best fit for sweetness and flavour perception, closely followed by the apparent viscosity at a shear rate of 50 s^{-1} (Table 3 and Figure 4).

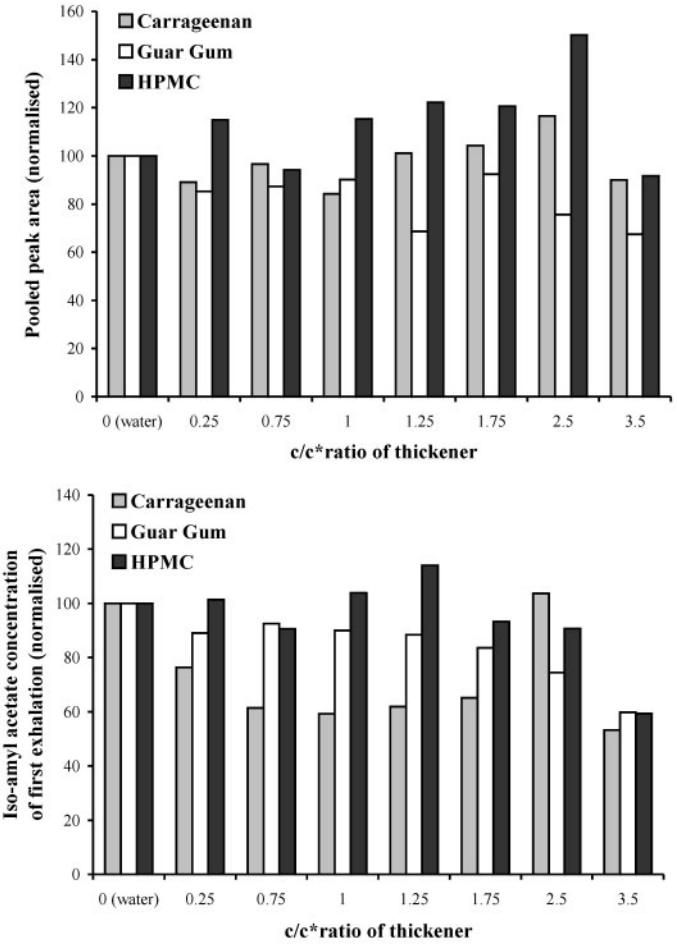


Figure 2. Real-time aroma release from the experimental samples, by API-MS. Data were normalized against release from water for each panellist, then averaged across all five panellists (two replicates for each solution). **(a)** Pooled peak area data and **(b)** first exhalation concentration data.

A two-factor ANOVA of the above c^* sweetness data (with log c/c^* and thickener type as factors) showed significant effects of both factors and a significant interaction term ($P < 0.05$; Table 4A). This indicates that the thickeners behaved differently with respect to sweetness suppression as the c/c^* ratio increased. The interaction graph generated by Design Expert (Figure 5) shows clearly that λ-carrageenan did not suppress sweetness as much as guar or HPMC, when comparing samples of the same c/c^* ratio.

The corresponding results for iso-amyl acetate flavour also showed a significant interaction between thickener type and c/c^* ratio ($P < 0.05$; Table 4B). HPMC had a greater suppressive effect on flavour perception than did guar or

Table 2. Sensory magnitude estimation scores for sweetness and flavour perception in viscous solutions

Thickener	Conc.	Panel ME score for sweetness		Panel ME score for banana flavour	
		Mean	SD	Mean	SD
Water	–	112	18.2	98.2	17.7
Guar	$c^*/4$	117	37.1	96.8	11.6
	$3c^*/4$	96.3	13.6	84.8	20.3
	c^*	96.8	17.9	86.0	10.3
	$5c^*/4$	95.5	12.2	90.7	15.2
	$7c^*/4$	83.0	11.0	68.8	13.7
	$10c^*/4$	73.1	15.9	67.3	16.9
	$14c^*/4$	58.8	16.0	58.0	23.6
HPMC	$c^*/4$	106	7.9	96.0	16.9
	$3c^*/4$	95.8	11.4	92.9	6.3
	c^*	103	21.9	98.8	20.4
	$5c^*/4$	87.4	9.9	86.3	23.5
	$7c^*/4$	85.7	12.1	70.5	22.1
	$10c^*/4$	64.0	15.9	47.8	24.1
	$14c^*/4$	59.6	15.7	39.0	14.7
λ-Carrageenan	$c^*/4$	105	20.9	92.3	14.0
	$3c^*/4$	96.5	11.5	90.5	17.2
	c^*	103	19.8	85.8	17.2
	$5c^*/4$	91.0	9.9	78.0	23.4
	$7c^*/4$	87.8	12.2	74.3	18.5
	$10c^*/4$	78.5	24.3	61.0	18.0
	$14c^*/4$	79.0	14.0	56.8	23.9

ME = Magnitude estimation. Sensory scores are based upon ten panellists tasting each solution twice for sweetness and twice for flavour appraisal.

λ-carrageenan in viscous solutions of the same c/c^* ratio (Figure 5B).

When using the oral shear stress as a factor in place of c/c^*, results for flavour perception showed only a significant effect of the oral shear stress ($P < 0.0001$), and no significant effect of thickener type or interaction terms (Table 4D and Figure 5D). For sweetness, there was no longer a significant interaction term, but thickener type was still significant ($P < 0.001$) in addition to the oral shear stress ($P < 0.0001$); Table 4C and Figure 5C). Guar gum had a more suppressive effect on sweetness, relative to its oral shear stress, than carrageenan or HPMC.

A two-factor ANOVA with interactions was computed from the raw sensory data for both sweetness and flavour (with thickener type and c/c^* ratio as categorical factors). Fisher's least significant difference (LSD) for comparing mean values was calculated to be 14.6 for sweetness and 15.7 for flavour. With reference to Table 1, mean sensory scores differing by more than the LSD values quoted were found to be significantly different from one another ($P < 0.05$). Thus, relative to the reference (in water), each hydrocolloid resulted in a significant reduction in perceived sweetness at the $3c^*/4$ concentration. For banana flavour, there were different behaviours with hydrocolloid type. HPMC and guar significantly reduced flavour perception relative to the reference at $7c^*/4$ and above. λ-Carrageenan had a significant effect at $5c^*/4$ and above.

Model validation experiment

Mean sensory scores for perceived sweetness and flavour of seven new samples (including xanthan and methyl cellulose thickened solutions) fitted closely with the original models based on oral shear stress (Table 5 and Figure 6). Incorporation of the new data resulted in only minor changes to the original models; indeed, the model for sweetness could be improved by including the new points ($R^2 = 0.88$).

Discussion

By comparing the sensory and in-nose aroma release experiments, the conclusion is that the drop in flavour perception which occurred above c^* (Figure 3) was not attributable to a drop in odour stimulus (in-nose iso-amyl acetate concentration) at the olfactory receptors. This is in agreement with

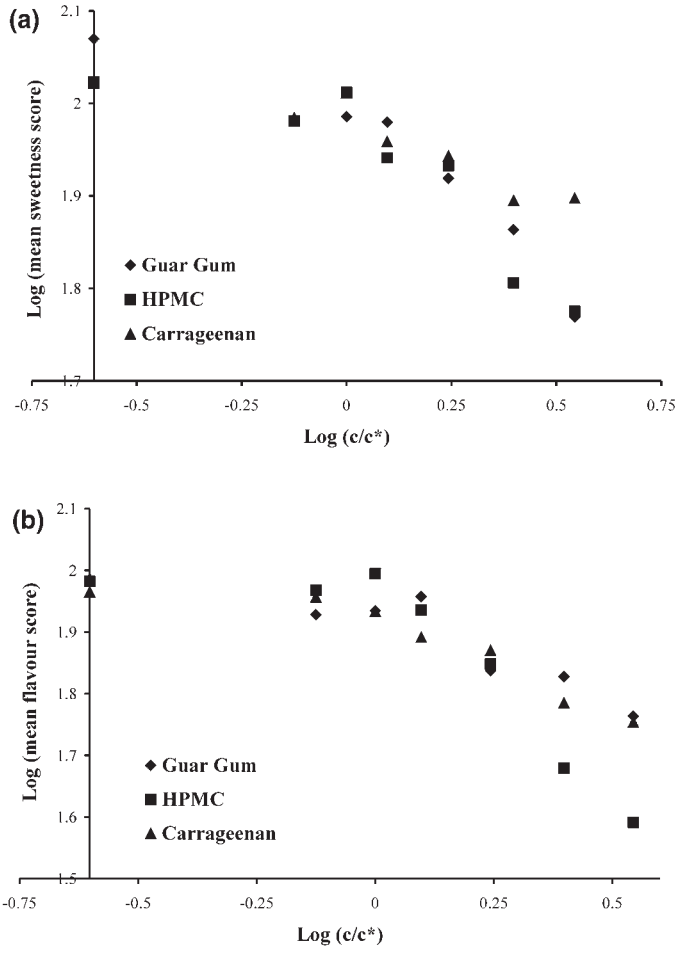


Figure 3. Perception of **(a)** sweetness and **(b)** iso-amyl acetate flavour plotted against hydrocolloid *c*/*c**.

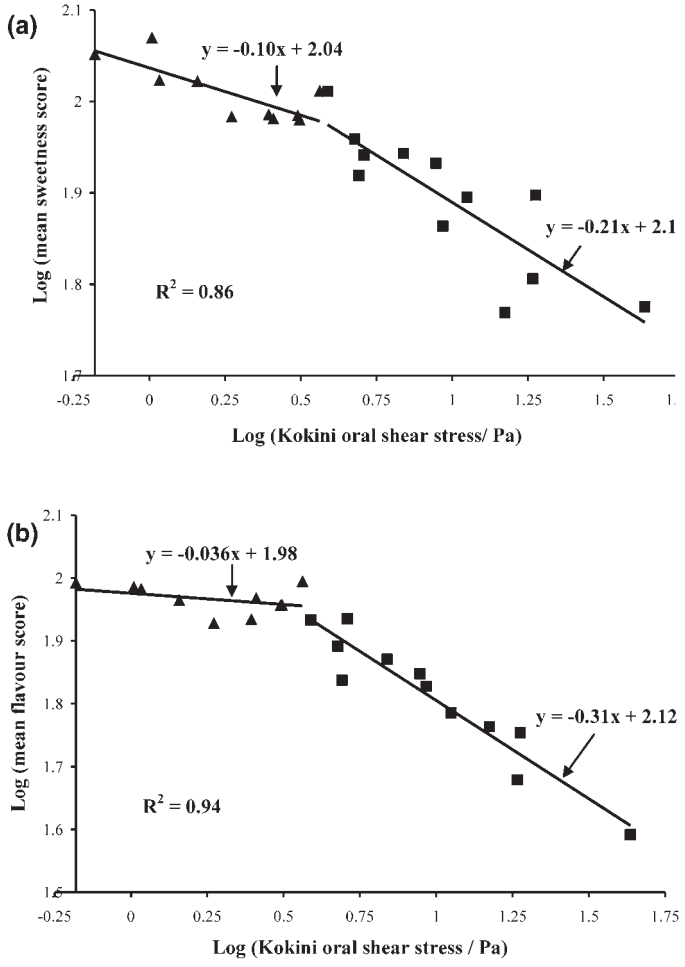


Figure 4. Perception of **(a)** sweetness and **(b)** iso-amyl acetate flavour plotted against the Kokini oral shear stress.

Table 3. Correlation coefficients for models relating the sensory perception of sweetness and flavour to rheological properties of the samples

Factor	R^2 for sweetness model	R^2 for banana flavour model
Kokini oral shear stress	0.86	0.94
c/*c**	0.85	0.84
Consistency index (m)	0.87	0.9
Zero shear viscosity	0.87	0.87
Apparent viscosity at 50 s^{-1}	0.85	0.93
Apparent viscosity at 100 s^{-1}	0.83	0.92

Models refer to two regression lines fitted to a plot of log (sensory perception) versus log (factor), corresponding to the below *c** and above *c** data (e.g. see Figure 4).

findings elsewhere (Hollowood *et al.*, 2002). Sensory perception began to drop off steeply at thickener concentrations above *c** (Figure 3). However, there was no corresponding reduction in aroma release in-nose, in terms of either concentration or total amount integrated over time. It is important to consider total area and first exhalation concentration data jointly (Figure 2), since both stimulus intensity and temporal aspects of release play a role in determining perceived odour magnitude (Overbosch, 1989; Baek *et al.*, 1999).

The first exhalation peak concentration of iso-amyl acetate in-nose was more or less constant, averaged across all panellists, up to the 10*c**/4 concentration of thickener. A reduction in mean in-nose concentration was observed at the 14*c**/4 thickener concentration, although this was not found to be statistically significant owing to the degree of variation inherent in nose-space release measurements (error bars are omitted from Figure 2 for clarity). This results from variations in swallowing pressure, and from individual differences in physiology and mouth movements (Burdach and Doty, 1987; Buettner and Schieberle, 2000). Thus, some panellists actually showed an increase in release from the most viscous solutions while others gave the opposite result; on average, there was no clear trend with thickener con-

Table 4. Two factor ANOVA of the sensory data above c*

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F*-value	Prob. > *F*	Significant factors
(A) Sweetness (factors = thickener type and *c*/*c** ratio)						
Block (by panellist)	0.098	9	0.011			
Model	0.897	5	0.179	24.9	0.0001	
A (*c*/*c** ratio)	0.766	1	0.766	106	0.0001	***
B (thickener type)	0.067	2	0.034	4.68	0.0109	*
AB (interaction)	0.064	2	0.032	4.45	0.0134	*
Residual	0.971	135	0.007			
Total	1.97	149				
(B) Flavour and *c*/*c** (factors = thickener type and *c*/*c** ratio)						
Block (by panellist)	1.06	9	0.118			
Model	2.26	5	0.451	22.1	0.0001	
A (*c*/*c** ratio)	1.81	1	1.81	88.6	0.0001	***
B (thickener type)	0.154	2	0.077	3.76	0.0257	*
AB (interaction)	0.294	2	0.147	7.21	0.0011	**
Residual	2.76	135	0.020			
Total	6.07	149				
(C) Sweetness (factors = thickener type and oral shear stress)						
Block (by panellist)	0.098	9	0.011			
Model	0.870	3	0.290	39.7	0.0001	
A (oral shear stress)	0.802	1	0.802	110.0	0.0001	***
B (thickener type)	0.130	2	0.065	8.93	0.0002	***
Residual	0.999	137	0.007			
Total	1.97	149				
(D) Flavour (factors = thickener type and oral shear stress)						
Block (by panellist)	1.06	9	0.118			
Model	2.15	3	0.716	34.2	0.0001	
A (oral shear stress)	1.99	1	1.99	95.4	0.0001	***
B (thickener type)	0.021	2	0.011	0.513	0.5998	
Residual	2.86	137	0.021			
Total	6.07	149				

ANOVA tabulated for log (mean sensory score) data, c* and above series. Variation due to panellist has been blocked. Model refers to Design Expert v. 6.0.2 fit to the data. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

centration. In contrast, trends in sensory perception were clear-cut and consistently fell in intensity with increased viscosity.

Sensory data plotted against thickener *c*/*c** (Figure 3) showed a similar form to previously published results (Baines and Morris, 1987, 1988; Hollowood *et al.*, 2002). However, above *c**, perceptual data for the three different hydrocolloids was correlated only loosely with the *c*/*c** ratio. Results of the ANOVA for both sweetness and flavour data above *c** (Table 4A,B) showed significant interactions between thickener type and *c*/*c** ratio, confirming that the behaviours of individual hydrocolloids differed when plotted against *c*/*c**.

The rheological factor which gave the best overall correlation with the sensory perception of sweetness and flavour was the Kokini oral shear stress (Table 3). Other rheological parameters, notably the apparent viscosity at a shear rate of 50 s^{-1}, showed good correlation with sensory data, in agreement with previous findings (Wood, 1968). This is not too surprising, since the oral shear stress is calculated from and thus related to some of the other factors investigated. Its advantage, relative to using estimates of oral viscosity based on one shear rate, is that it accounts for the shear-thinning nature of hydrocolloids over a range of shear rates, providing a better model for the range of shear rates encountered in the oral evaluation of viscosity (Shama and Sherman, 1973; Christensen and Casper, 1987). An added attraction of using the oral shear stress to model sensory data is that it has been shown to be the stimulus involved in the oral evaluation of viscosity (Elejalde and Kokini, 1992) and thus has real meaning in a somatosensory sense.

ANOVA of the above *c** data (Table 4D) showed that banana flavour perception could be predicted solely from the oral shear stress, with no significant effect of thickener type. Thus, relating flavour perception to the oral shear stress removed the variation between hydrocolloids that was evident in the *c*/*c** model (Table 4B). The situation was not

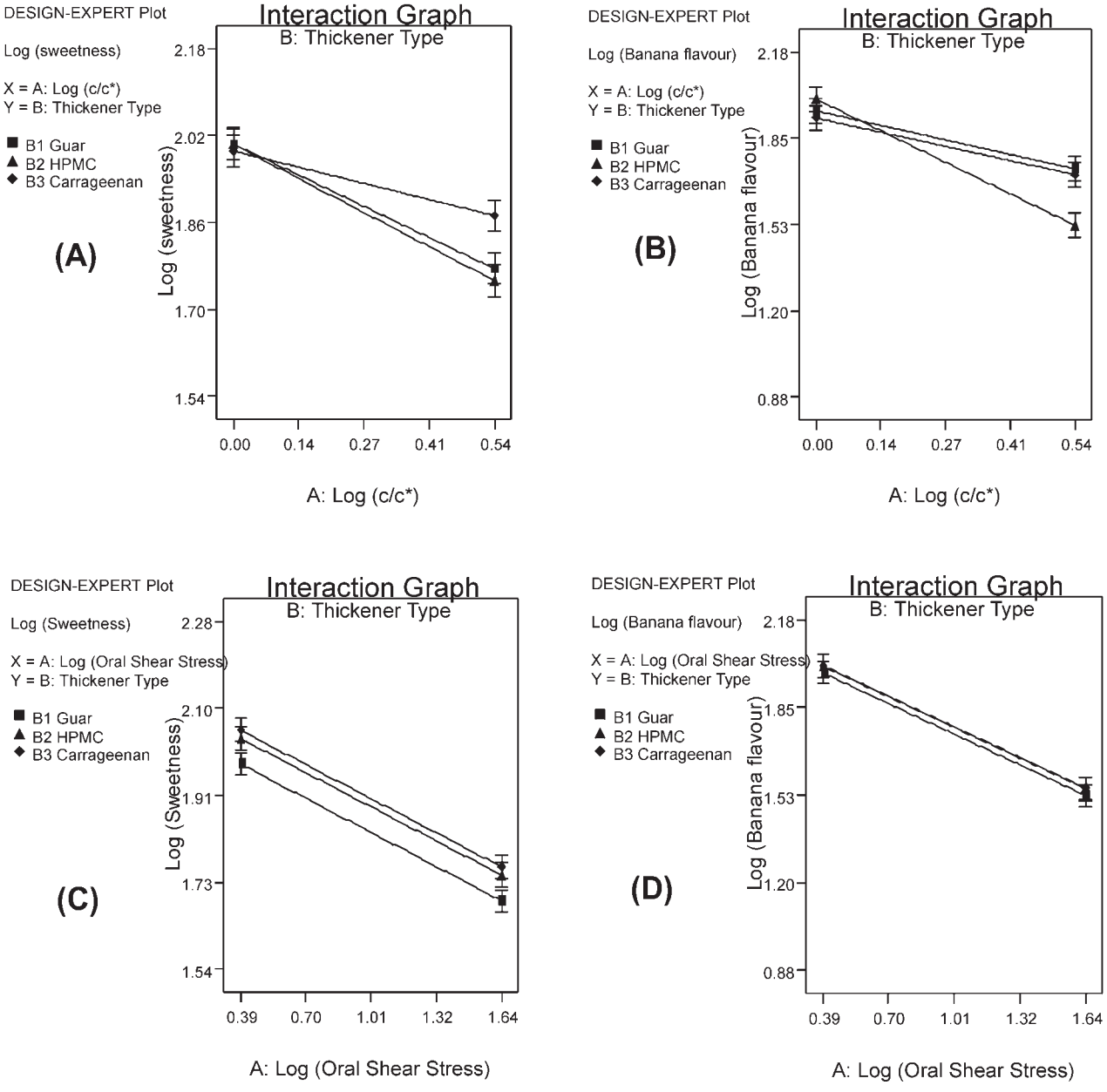


Figure 5. Design Expert interaction plots of sensory data above *c**. **(A)** Sweetness and *c*/*c**; **(B)** flavour and *c*/*c**; **(C)** sweetness and oral shear stress; **(D)** flavour and oral shear stress.

as clear cut with sweetness perception. Although looking at sweetness in terms of the oral shear stress removed the interaction term from the model (Table 4C), there was still a significant effect of thickener type (guar gum suppressing sweetness slightly more than HPMC or λ-carrageenan in samples of similar oral shear stress). One factor that could contribute to this discrepancy is the question of individual taste of the hydrocolloids (Izutsu and Wani, 1985). Whilst the hydrocolloids used in the investigation were of high purity and selected on the basis of their relative tastelessness, an appraisal of the taste of hydrocolloid solutions in isolation was not included in our research. Although subtle differences in taste due to hydrocolloid type cannot be ruled out as a source of minor variation in the taste data, we would not have expected the thickeners all to behave so similarly if there were substantial taste components present. Such taste effects would be expected to be both concentration and hydrocolloid dependent, yet although the concentrations of individual thickeners ranged from, for example, 3.4 g/l of guar to 10 g/l of HPMC in the 7*c**/4 samples, the sweetness suppression was of the same order of magnitude for each (Table 2). It seems reasonable to conclude that the taste component of hydrocolloids might account for subtle differences in behaviour between thicken-

Table 5. Rheology and sensory results from the model validation experiment

Thickener	Conc.	Consistency index '*m*' (mPas^n)	Power law index '*n*'	Oral shear stress (τ/Pa)	Panel ME score for sweetness	Model residual (predicted – actual sweetness)	Panel ME score for flavour	Model residual (predicted – actual flavour)
Guar gum	18c*/4	5391	0.37	19.2	63.3	–4.4	55.5	–2.8
HPMC	12c*/4	4304	0.62	27.9	61.8	–0.8	55.5	–8.5
Xanthan gum	1.0 g/l	95.2	0.50	1.72	101	–3.1	91.0	2.7
	4.0 g/l	1997	0.24	5.96	80.8	–5.7	76.0	–0.2
	7.5 g/l	7168	0.15	12.7	68.3	–5.5	55.8	4.1
Methyl cellulose	4.0 g/l	47.8	0.84	3.22	103	5.0	85.8	5.8
	8.0 g/l	953	0.60	10.1	73.3	–4.2	65.3	–0.9

ME = Magnitude estimation. Sensory scores are based upon 10 panellists tasting each solution twice for sweetness and twice for flavour appraisal.

ers, but is not the principal factor involved in sweetness reduction.

The perceptual models based on the oral shear stress, which had been developed in the main experiment, were sufficiently robust to predict the sweetness and flavour suppressing behaviour of the additional hydrocolloids used in the model-validation experiment (Table 5). The final models (Figure 6) thus adequately described the behaviours of five different hydrocolloids. The prediction of flavour perception from xanthan solutions is of particular note, since it demonstrates that the concepts involved can be applied to thickeners other than random-coil polysaccharides. Xanthan adopts a rod-like conformation in solution, and the ability of these rods to align under shear is thought to explain the particularly shear-thinning nature of the gum (Cuvelier and Launay, 1986). This behaviour is taken into account when predicting oral shear stress, so for a specified zero-shear viscosity, the oral shear stress would be much lower for xanthan than for HPMC or guar gum. This may well explain the reportedly good flavour release properties of xanthan (Baines and Morris, 1988).

Significantly, we still observe an inflection in perception when plotting sensory data against the oral shear stress, at around $\tau = 3.7$ Pa (the point on the oral shear-stress axis corresponding to c^*). This inflection might arise from two linear effects of differing origin, which have first a gradual and then a more drastic effect on flavour perception. Such effects might be physical (e.g. reduction in tastant mass transfer; blocking of receptor sites by hydrocolloid), neurological (complex integration of signals at multi-modal neurons) or psychophysical (a result of higher cortical processing) in nature.

The overall pattern of our results seems to be readily

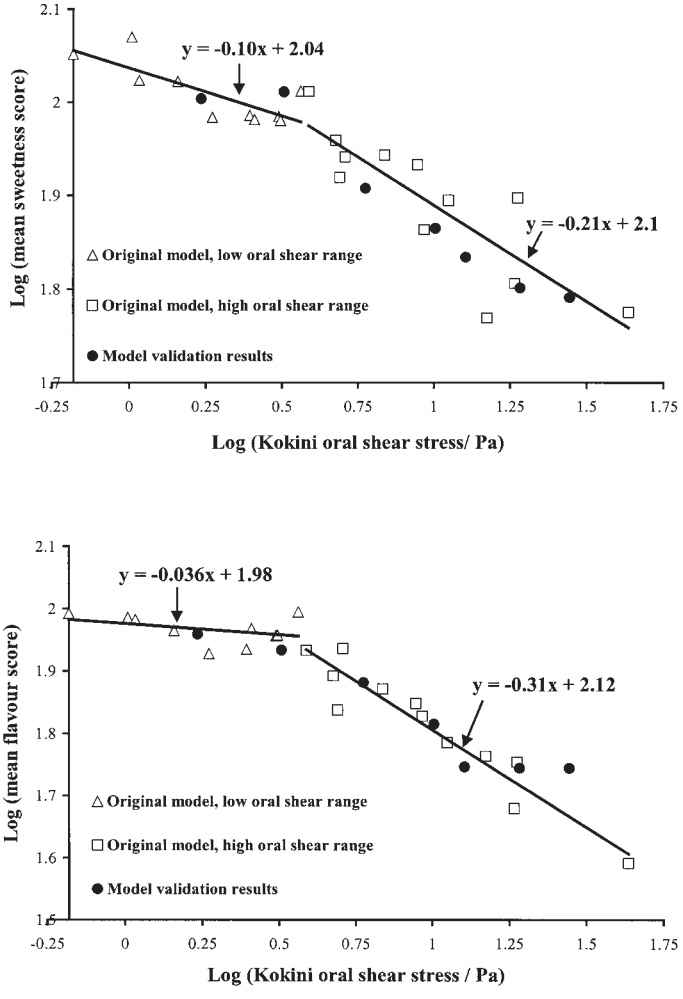


Figure 6. Model validation: data from Table 4, showing the fit with original perceptual models.

reproducible (Baines and Morris, 1987; Hollowood *et al.*, 2002). It may be that what we are seeing is the interplay between the senses of taste, aroma and texture as viscosity is manipulated in a model system. Since iso-amyl acetate flavour perception decreased in the presence of a consistent in-nose stimulus, it is feasible that a perceptual mechanism, or interaction of the senses, is operative. Evidence of taste–aroma interactions is now well documented (Noble, 1996) in situations where there is 'congruency' between the taste and aroma concerned (Schifferstein and Verlegh, 1996). This is clearly the case for iso-amyl acetate and sweet taste. The observed suppression of iso-amyl acetate flavour in the presence of viscous stimuli may be explained by this taste–aroma interaction, with the drop in perceived sweetness driving the perception of a congruent aroma (Hollowood *et al.*, 2002). Taking this concept further, and bearing in mind that the shear stress developed in-mouth is the stimulus for the oral perception of viscosity (Elejalde and Kokini, 1992), our data supports the possibility of a sensory input for viscosity that is a part of the flavour experience of foods. Somatosensory information might then interact at a neural or psychological level with the perception of taste and aroma to produce texture–taste– aroma interactions.

Alternatively, our models based on oral shear stress may work simply because they take into account the individual shear-thinning characters of the hydrocolloids (exemplified by m and n). These parameters might adequately predict an underlying physical mechanism for the reduction in sweetness. For example, if shear-thinning behaviour controlled the flux of tastant molecules across a boundary layer of fluid to the tongue's surface, then it might predict taste perception for mass transfer reasons, rather than by altering oral shear stress. The drop in aroma perception would then be attributed to a reduced taste–aroma interaction between sweetness and a sweet-associated volatile (e.g. iso-amyl acetate). To explore this possibility, we used the technique of Cussler *et al.* (Cussler *et al.*, 1979) to model our results for sweetness against theoretically derived diffusion coefficients for the respective solutions (Clough *et al.*, 1962) (data not shown). Correlation was very poor ($R^2 < 0.2$), suggesting that diffusion/mass-transfer considerations alone were insufficient to explain the observed changes in perception.

To look at the nature of texture–taste–aroma interactions more closely, we re-examined data from Hollowood *et al.* (Hollowood *et al.*, 2002). This experiment modelled sweetness and flavour perception using a large three-factor design of solutions thickened with HPMC, sweetened with sucrose and flavoured with benzaldehyde. Looking first at non-thickened samples containing 100 p.p.m. benzaldehyde, we plotted the sucrose–benzaldehyde interaction in aqueous solution (Figure 7). Over the 30–50 g/l range of sucrose, the increase in benzaldehyde flavour was practically linear with increasing sweetness perception. We then identified thickened solutions containing 50 g/l sucrose which the model predicted to be iso-sweet to aqueous solutions of

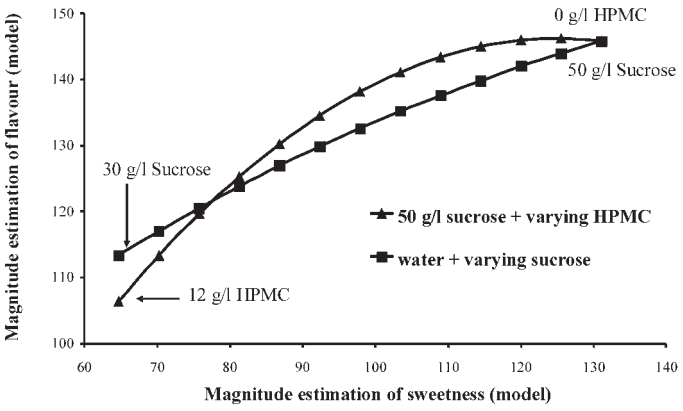


Figure 7. Benzaldehyde flavour perception in iso-sweet HPMC or aqueous solutions (data from Hollowood *et al.*, 2002).

30–50 g/l sucrose and plotted the resultant flavour perception on the same axes (Figure 7). It can be seen that iso-sweet solutions did not lead to the same benzaldehyde flavour score when one was presented in water and the other was thickened and its sweetness partially suppressed by HPMC. Initially, as HPMC was added to the system (increasing from right to left in Figure 7), the flavour score for the HPMC solution remained higher than would have been estimated on the basis of a pure sweetness–aroma interaction. Subsequently, at ~10 g/l HPMC, the hydrocolloid system came to have a lower flavour intensity than would have been estimated from the results for the aqueous system. Clearly, these discrepancies suggest that taste–aroma interactions alone are not driving the reduction in flavour perception. A more complex integration of the senses might explain this interplay of texture, taste and flavour.

There is considerable neurological evidence to support functional convergence of sensory information relating to taste, olfaction and somatosensory stimuli. Cerf-Ducastel *et al.* (Cerf-Ducastel *et al.*, 2001) provided a recent overview of the evidence from neurological studies in both rodents and primates. They concluded that there is clearly a functional convergence of the gustatory, lingual somatosensory and olfactory inputs, which together constitute the neural substrate for a multimodal representation of flavour information. Sensory pathways are known to overlap widely from the periphery, so that gustatory nerves, including the chorda tympani, may respond to both taste and tactile stimulation, originating simultaneously during food intake. Related fields of research are concurrently developing theories founded in a multi-sensory approach to perception. Driver and Spence (2000) described cross-modal integration of sensory information and considered this to be the rule, rather than the exception, in real-world perception.

So, if flavour is a multimodal percept, arising from signals sharing common neural pathways, integrated and interpreted by the brain through a logical process aimed at

optimal decision making, it should come as little surprise that changes in one stimulus can impact on the perception of another. The results presented here can thus be viewed as complementary to contemporary views on the multimodal nature of flavour perception.

Conclusions

Aroma and flavour perception in hydrocolloid thickened solutions can be predicted by the Kokini oral shear stress. This supports the hypothesis that a sensory signal for viscosity, corresponding to the shear stress generated in-mouth, can modulate the perception of taste and aroma. Equally, the success of the models developed here may result from physical effects related to the power law properties of fluids, which are incorporated in the calculation of oral shear stress. Either way, the success of Elejalde *et al.* (Elejalde *et al.*, 1992) in applying the Kokini model to the perception of thickness in real foods suggests that the principles involved might be applicable when studying flavour perception in more complex systems.

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