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Flavour Perception: Aroma, Taste and Texture Interactions

Carole Tournier • Claire Sulmont-Rossé • Elisabeth Guichard*

UMR1129 FLAVIC, INRA, ENESAD, Université de Bourgogne, 17 rue Sully, 21000 Dijon, France

***Corresponding author*: * guichard@dijon.inra.fr**

ABSTRACT

Flavour perception is determinant for the acceptability of food products by consumers. Aroma and taste play an important role in flavour perception and it is well known that the chemical composition of the matrix and consequently its structure influences release and perception of flavour. However, from simultaneous measurements of human perception and physical concentration *in vivo*, texture – aroma and texture – taste interactions are not always explained by physico-chemical mechanisms. Moreover aroma – taste interactions have been the subject of many studies already reviewed and are mainly explained by cognitive interactions even if in some case physico-chemical mechanisms may occur. Finally, few studies mentioned the impact of aroma and taste on texture perception. The aim of this review is to focus on the impact of aroma, taste and texture interactions on flavour perception. For each type of binary interactions (texture – aroma, aroma – texture, texture – taste, taste – texture, taste – aroma and aroma – taste) we will present a short state of the art and the mechanisms that could be involved in the interactions: physico-chemical and cognitive mechanisms. The mechanisms of aroma – taste and taste – aroma interactions are known to mainly depend on learning association. However, the mechanisms involved in texture – flavour and flavour – texture interactions are more complex and need further developments to understand the part explained by flavour partition in the product, flavour release in the mouth after food breakdown and cognitive interactions.

Keywords: cognitive mechanisms, cross-modal interactions, physico-chemistry

CONTENTS

INTRODUCTION

Flavour is defined as a "complex combination of the olfactory, gustatory and trigeminal sensations perceived during tasting. The flavour may be influenced by tactile, thermal, painful and/or kinaesthetic effects" (AFNOR 1992). However the exact mechanisms that lead to our perception of flavour have not yet been elucidated, due to different reasons (Taylor and Roberts 2004): i) flavour perception involves a wide range of stimuli, ii) the chemical compounds and food structures that activate the flavour sensors change as food is eaten, iii) the individual modalities interact in a complex way. There is a need first to identify not only the stimuli involved in flavour perception which include taste and aroma modalities, but also the other senses which can affect flavour perception, such as irritation, temperature, color, texture, sound, which were reviewed by Delwiche (2004). It has been shown for example that irritants do interact with the perception of both tastes and smells inhibiting their perceived intensity and that some taste and odor compounds contain an irritative component (Cain 1974). Temperature has an impact on taste perception through the triggering of cascade reactions in receptors (Cruz and Green 2000). In the case of color, learned color – taste associations influence perceived taste (Pangborn and Hansen 1963). All these sensations experienced while eating are crucial and should have a tremendous impact on whether foods will be accepted or rejected. Moreover, one has also to take into account the influence of the associations between flavour experiences and feelings of contentment or well-being on the overall acceptability of the product (Blake 2004). This process starts even before birth when the foods eaten by the

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mother influence the olfactive environment of the growing foetus (Schaal *et al.* 2000). However flavour preferences and related food liking are not solely and linearly programmed by early experiences. Instead they are enriched and further reorganised by multiple influences outside the restricted mother-infant context, in peer groups, evolving with age, and under the pressure of incentives afforded by the surrounding culture at large (Schaal 2006). For adults, the changes in life may directly affect food choices and thus modify flavour preferences (Bove *et al.* 2003). In recent years there has been rapid progress in the understanding of how the human brain develops and grows. The plasticity of the brain allows human beings to be uniquely adaptable to their environment, but this takes time and that is why the human infant takes so long to reach adulthood. Besides the understanding of the consequences of the learned experiences on food acceptability, there is a need to better understand flavour perception during food consumption.

The present review will mainly focus on texture – taste – aroma interactions. Once the food has been transferred to the mouth, the different processes that occur during mastication alter the physical properties of the food and will affect the perception of texture and flavour (aroma and taste). Reciprocally, taste and aroma perceptions may affect the perception of the food texture.

Texture is a sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of vision, hearing, touch and kinaesthetic (Szczesniak 2002). Oral texture is the perception that arises when food interacts with teeth, saliva and tactile receptors in the oral cavity. During mastication the texture of the food changes, the palatability of the food is assessed and the food converted to a form suitable for swallowing (Mishellany *et al.* 2006). The process of mastication varies among people and this affects the food breakdown and subsequently texture and flavour of the food (Brown and Wilson 1997). From liquids to gels, there is a wide range of rheological properties generating complex feelings in the mouth, such as stickiness, thickness, smoothness, slipperiness and this perceived texture can influence flavour perception, as already reviewed (Lubbers 2006).

Considering taste perception, it is widely accepted that there are at least five major categories of tastes: sweet, sour, salty, bitter and umami. All these taste qualities can be elicited from the regions of the tongue (**Fig. 1**) that contain taste buds (Smith and Margolskee 2001). Recent molecular and functional data have revealed that, contrary to popular belief, there is no tongue map and that the five basic modalities are perceived in all areas of the tongue (Chandrashekar *et al.* 2006). The chemical signal carried by the stimulus is converted to an electric impulse that is sent via afferent nerve to the nucleus of the solitary tract and ultimately to cortical regions of the brain (Linderman 2001). There are thousand of chemically distinct nonvolatile compounds that elicit taste (Rawson and Li 2004). Although salt taste is elicited by many ionic tastants, it is mostly relevant to sodium and one mechanism for salt detection is the amiloride-sensitive epithelial sodium chanel ENaC (Kretz *et al.* 1999). Sour taste is due to the concentration of hydrogen ions in solution and acidic stimuli elicit action potentials (APs) from taste cells in a dose dependant manner based on the titratable acidity of the stimulus rather than its pH (Gilbertson *et al.* 1992). Sweet taste perception due to sucrose or artificial sweeteners, is initiated by the interaction of a sweetener with G protein-coupled taste receptors in the apical part of Taste Receptor Cells. There has been great progress in the understanding of sweet taste genetic in the past few years. Proteins from the T1R family combine at the surface of the TRC to produce functional receptors. Bitter taste is generated by tastants such as quinine and 6-n-propyl-2-thiouracil (PROP). Only a few receptors have been characterised functionally in human. Umami taste is generated by amino acids such as L-glutamate which is known to bind G protein-coupled receptors and activates second messengers.

The volatile compounds responsible for odours and aroma belong to a large variety of chemical classes, such as alcohols, ketones, esters, phenols, lactones. There is a consensus to see odour representation in the olfactory epithelium as a combinatorial process (Malnic *et al.* 1999). A large family of odorant receptors (ORs) as G protein-coupled receptors were identified which allowed considerable progress towards a comprehensive understanding of the molecular basis of olfaction (Buck and Axel 1991). A 3-D molecular modelling study on the measured affinity of different ligands for a human receptor was used to explain the experimental affinities by molecular descriptors and then to predict agonist or antagonist effects of other odorants (Tromelin *et al.* 2006). Great steps have been achieved in the understanding of odour sensing, but the delivery dynamics of the airborne molecules to the olfactory epithelium still needs to be deciphered, in particular the mechanism regula-

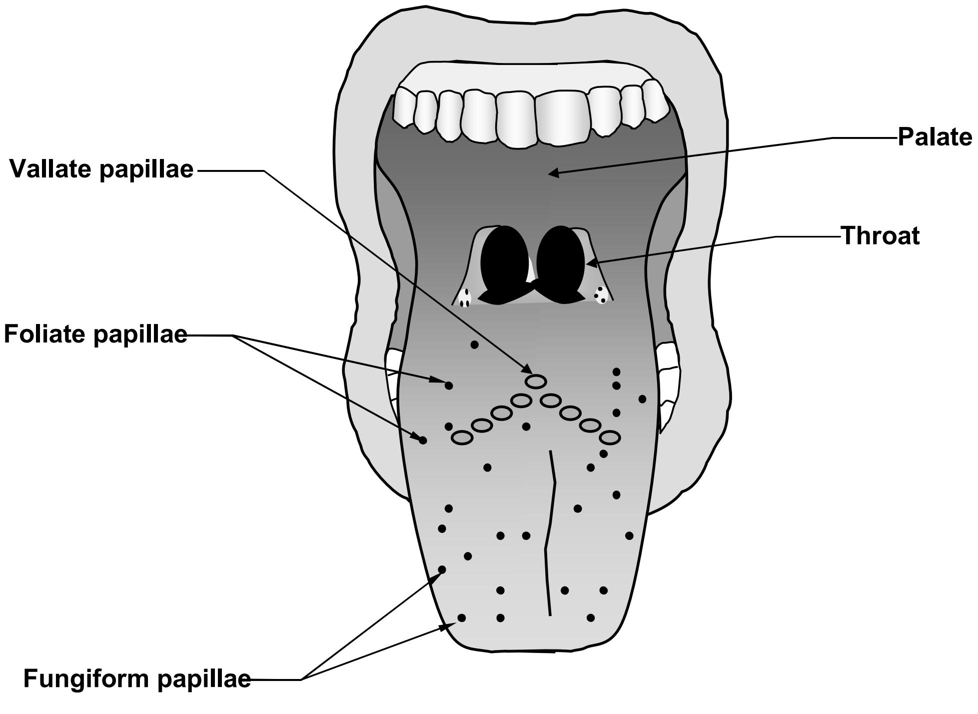

Fig. 1 Representation of the oral cavity and the repartition of taste papillae on the tongue.

ting odour perception which can occur either by the odorant capture level or further during neural signal coding and treatment (Pernollet and Briand 2004).

The sensory systems controlling food intake are particularly rich and complex. They allow consumers to identify many physicochemical properties of food with great precision but even though distinct, these sensory systems interfere with each other at several anatomical and functional levels. An overview of the flavour interactions at the sensory level has recently been done (Keast *et al.* 2004), considering four levels of interactions: chemical interactions occurring in the food matrix, mechanical/structural interactions during mastication, peripheral physiological interactions and cognitive interactions. In the present paper we will present some examples of texture – flavour, flavour – texture then taste – aroma interactions and discuss their origins. Because these three modalities involve different kinds of receptors, it seems unlikely that texture – taste – aroma interactions occur at a receptor level (Noble 1996; Paçi Kora *et al.* 2003). Our review will mainly focus on the respective influence of physico-chemical mechanisms (molecular interaction, food structure, *in-vivo* destructuration) and cognitive mechanisms that may contribute to texture – taste – aroma interactions.

IMPACT OF TEXTURE ON FLAVOUR PERCEPTION

State of the art

Texture – taste and texture – aroma interactions have been the subject of numerous studies these last decades, first carried out on simple model systems and then on model food systems of increasing complexity, close to real food formulations. The objectives of these studies mainly consisted in the addition of texturing agents to the system containing taste compounds and/or aroma compounds, in order to obtain a defined structure of the food system (validated by rheological measurements) and thus a resulting texture perceived in the mouth. These texturing agents are mainly hydrocolloids such as starch, gelatin as well as various gums (guar, carboxymethylcellulose (CMC), hydroxypropylcellulose (HPC), xanthan, carrageenan) widely used in the food industry. Depending on the nature of the hydrocolloids, two types of systems can be obtained: a thickened solution (characterised by its viscosity) or a gelled system (characterised by its gel strength).

It is nowadays admitted that texture influences flavour perception and that an increase of hydrocolloids concentration generally leads to a decrease in aroma and taste perception. Concerning thickened solutions, the studies published by Pangborn and collaborators are often cited as an example of the impact of the viscosity on taste and aroma perception. For example, in solutions containing different taste compounds, an increase of viscosity with addition of xanthan induced an increase of the viscosity perceived in the mouth but also a decrease in perceived sweetness intensity of sucrose solutions, sourness intensity of citric acid solutions and bitter intensity of caffeine solutions (Pangborn *et al.* 1973). Moskowitz and Arabie (1970) used the magnitude estimation methodology and observed that increases in viscosity imparted by CMC generally decreased the taste intensities of solutions of glucose, citric acid, sodium chloride and quinine sulphate. Increasing viscosity through the addition of thickeners was also found to result in a decrease in perceived intensity of volatile components. For example, addition of xanthan in solution was also found to decrease aroma intensity of butyric acid and dimethyl sulfide (Pangborn and Szczesniak 1974). In model soups, addition of hydroxypropylmethylcellulose (HPMC) was reported to decrease basil intensity (Ferry *et al.* 2006). So, in thickened systems it is generally understood that an increase in thickener content induces a decrease in perceived intensity of volatile and non volatile compounds (Arabie and Moskowitz 1971; Pangborn *et al.* 1978; Christensen 1980a; Mälkki *et al.* 1993).

This impact of thickening agents on perceived flavour intensity is not a linear phenomenon. Indeed the main effect of thickeners is a modification of the viscosity above its critical coil overlap concentration (c*) which coincides with a marked decrease in flavour perception. Indeed taste and aroma perceived intensity were modified only when the thickener is present at a concentration higher than its critical concentration c*. Below the c* value, the presence of macromolecules did not affect flavour perception (Baines and Morris 1987; Cook *et al.* 2002; Hollowood *et al.* 2002).

For gel model systems, the impact of gelling agents on flavour perception is similar to those observed for thickened solutions. For example, Lundgren *et al.* (1986) worked on pectin gels containing sucrose, citric acid and an orange aroma. When pectin content increased from 1.48 to 2.77% (w/w), gels were perceived firmer and also less sour, less sweet and less intense in aroma. Similar results were observed with other gelling agents and other taste compounds (Chai *et al.* 1991; Costell *et al.* 2000) as well as other aroma compounds (Kälviäinen *et al.* 2000; Juteau *et al.* 2004; Boland *et al.* 2006). Time-Intensity methodology was used to study the impact of gels texture on temporal flavour perception. In firmer gels, results showed a lower perceived maximum intensity as well as a longer time to reach this intensity compared to softer gels (Guinard and Marty 1995; Wilson and Brown 1997; Baek *et al.* 1999). As a conclusion, studies previously cited showed that an increase in the viscosity or the strength of the gel induced a decrease in taste and/or aroma perception.

Nevertheless the impact of texture on flavour perception is clearly dependant on the nature of taste and aroma compounds. For example in Pangborn *et al.* (1973) the addition of xanthan induced a decrease in sweet and sour intensity but did not affect saltiness perception of sodium chloride solutions. In another study, the addition of HPMC at a concentration above c* was found to change the intensity of sweet and salty tastes but did not change sour and bitter tastes (Cook *et al.* 2002). Finally, increasing pectin content from 1 to 4% affected sourness intensity but not sweetness intensity (Guichard *et al.* 1991). These different behaviours observed among taste sensations were also observed for a same taste produced by different molecules. For example, in different sweetener solutions presenting equivalent sweetness in plain water, the reduction of sweetness intensity by hydrocolloids (CMC, guar gum and oat gum) was found to be the most important for sucrose (10%) intermediary for fructose (9%) and the weakest for aspartame (0.13%) (Mälkki *et al.* 1993). A decrease of sweetness intensity with addition of maltodextrins (5 mPa.s viscosity) was observed for a solution of sucrose but not for a solution of glucose (Portmann *et al.* 1992).

Concerning aroma perception, numerous studies showed an effect of the nature of aroma compounds. For instance, Pangborn and Szczesniak (1974) added sodium alginate in aroma solutions and observed a decrease of butyric acid intensity, no effect on acetophenone intensity and an increase of acetaldehyde intensity. In sourmilk, gelatin addition induced a decrease in fruity intensity of 2-methyl-butanoic acid but had no impact on maltol intensity (Wendin *et al.* 1997). Finally, the overall intensity and garlic note of flavored solutions (1-octen-3-ol (mushroom), diallyl disulfide/diallyl sulfide (garlic), and diacetyl (buttery)) was perceived less intense in a 0.3% guar gum compared to a solution without gum but the mushroom and buttery notes were not affected by the increase of viscosity (Yven *et al.* 1998).

Texture – flavour interactions also depend on the nature of the texturing agent. For example, Pangborn *et al.* (1978) modified the viscosity of orange juice by varying the nature (5 hydrocolloids) and the concentration (5 concentrations) of the texturing agents. Reduction of sweetness perception by addition of hydrocolloids was found to be the highest for xanthan gum and the weakest for CMC-Low viscosity. Similar results were observed by the authors for aroma intensity (Pangborn and Szczezniak 1974). Stone and Oliver

(1966) observed that the detection threshold of sucrose was lower in a CMC solution compared to a starch solution. Finally, custard desserts composed of λ-carrageenan were perceived sweeter than those containing the same amount of ι-carrageenan (Lethuaut *et al.* 2003). In gelled candies, Kälviäinen *et al.* (2000) found a higher strawberry intensity in pectin gels, intermediary in starch gel and lower in gelatin gel. Similar results were observed by Cayot *et al.* (1998) who showed different isoamyl acetate intensities as a function of starch chemical nature. In these studies it seems to be difficult to understand the part of the interaction due to changes in the chemical composition and the part due to physical modifications of the structure.

The numerous studies previously cited highlight a combined effect of the structure and the composition of the matrix on flavour perception. Other studies proposed to vary these two parameters independently. To test the effect of composition only, Mälkki *et al.* (1993) compared different thickeners in solutions realized with similar viscosity (230 mPa.s). Solutions composed of oat gum were perceived sweeter than solutions composed of CMC. Depending on their nature, textural agents had different influences on sweetness perception of iso-viscous sucrose solutions (Christensen 1980a) and of sodium Sucaryl gels with similar hardness (Marshall and Vaisey 1972). Again, at similar rheological properties, a modification of the composition of model systems was found to affect aroma intensity of apple juices (Walker and Prescott 2000), basil soups (Ferry *et al.* 2006), chocolate milk beverages (Yanes *et al.* 2002). Finally, using Time Intensity methodology, Guinard and Marty (1995) observed that dynamic perception of benzaldehyde, δ-limonene and ethyl butyrate was different for starch, gelatin and carrageenan gels presenting the same hardness. There is a need to understand the mechanisms involved in aroma release and perception in order to explain the observed phenomena.

To test the effect of the structure, Saint-Eve *et al.* (2004) studied the impact of texture on flavour perception of low fat yoghurts presenting the same chemical composition. The authors observed that a decrease in viscosity (obtained via a mechanical treatment) has an exhausting effect on sweetness perception and also increases the intensity of the strawberry aroma in 4% fat yoghurt (Saint-Eve *et al.* 2006). This phenomenon was observed neither by Paçi Kora *et al.* (2003) who found no impact of the variation of viscosity on taste and fruity aroma perception of low-fat yoghurt with the same composition nor by Tournier (2006), who observed that decreasing the viscosity of model custard desserts had no impact on aroma perception but only induced an increase in sweetness perception.

Mechanisms at the origin of texture – flavour cross-modal interactions

Various mechanisms have been proposed to explain the impact of texture on flavour perception in complex foodstuffs. These mechanisms mainly focused on the effect of the composition in macromolecules, which induces molecular interactions, and on the state of organisation of the matrix, which limits the exchanges between the different phases: liquid or solid and vapour, through the establishment of a three-dimensional network (Lubbers 2006). In complement to the previous review, we will highlight in this chapter in a non-exhaustive manner, the different mechanisms at the origin of texture – flavour interactions, either physico-chemical mechanisms or cognitive mechanisms.

Physico-chemical mechanisms

In the food matrix: The addition of textural agents in the system modifies not only the composition but also the structure (and thus the perceived texture in the mouth). These modifications may affect the release of aroma and taste compounds from the food matrices. Two phenomena have been proposed, the nature of the macromolecule which affects aroma retention due to the different types of molecular interactions involved (Guichard 2002) and the structure of the matrix which affects the diffusivity and mass transfer coefficients of the volatile compounds (Voilley 2006). Since a few years, several authors have also observed that physiological mechanisms occurring during mastication may also influence aroma release and perception (Pionnier *et al.* 2004).

Molecular interactions: At the molecular level, hydrocolloids may interact in various ways with aroma compounds (Guichard 2002; Delarue and Giampaoli 2006). Molecular interactions include hydrogen bonding, London interactions, hydrophobic interactions or molecular inclusion, depending on the macromolecules. Yven *et al.* (1998) observed a decrease of 1-octen-3-ol release in xanthan solution which has been explained by the observation with exclusion chromatography of hydrogen bonding between the aroma compounds and the hydrocolloid. Van der Waals interactions were supposed between methylketons and low esterified pectinates (Braudo *et al.* 2000). Finally aroma compounds may be retained by inclusion complex with amylose of starch (Rutschmann and Solms 1990). In food matrices where starch is used as a gelling or texturing agent, the retention of aroma compounds depends on the amylase/amylopectine ratio of starch which influences the formation of complexes and the viscosity (Arvisenet *et al.* 2002). However, aroma retention and release depend on the nature of the compounds together with the nature of textural agents. For example, Roberts *et al.* (1996) studied the dynamic release of various aroma compounds from thickened solutions using a vessel simulating mouth conditions. Solutions were thickened with CMC and Guar gum adjusted to a same viscosity (160 mPa.s). Compared to water, these CMC and guar gum showed decreases of 36 and 44%, respectively for the release of α-pinene and of 58% and 63% respectively for the release of ethyl 2-methylbutyrate. More recently Gallardo-Escamilla *et al.* (2007) showed that addition of propylene glycol alginate and carboxymethyl cellulose in yoghurt produced a significantly higher thickness but with a less intense aroma perception which was explained by a reduced concentration of key volatiles in the headspace of these samples. Lubbers *et al.* (2007) used a quantitative structure-property relationship approach to understand which types of interactions were involved between aroma molecules and thickeners macromolecules in a model dairy gel. Twenty molecular descriptors of volatile compounds were significantly correlated with their retention in the gels and the surface-weighted negatively charged partial surface area seemed to play a critical role in the retention of aroma compounds in the different gels.

Contrary to aroma compounds, relatively less attention has been accorded to taste-hydrocolloids bindings. Hypothetical molecular interactions between taste components and textural agents and their impact on taste release have not been clearly demonstrated yet (Cook 2006).

Physical state and structure: The state of organisation of the matrix, caused by macromolecules, results in a more or less dense entanglement or a three dimensional network, established between a more or less significant number of macromolecule chains. The presence of this network can generate the reduction in the diffusivity of volatile compounds, slowing down their migration to the matrix-air interface (Lubbers *et al.* 2003; Juteau *et al.* 2004).

In thickened systems, taste and aroma intensities were greatly affected by the addition of hydrocolloids above their critical coil overlap concentration (c*) (Baines and Morris 1987; Cook *et al.* 2002; Hollowood *et al.* 2002), which is the concentration of hydrocolloids at which individual polymer chains interpenetrate. The decrease in flavour perception was attributed to an inefficient mixing due to polymer entanglement. Few studies investigated the impact of textural agents on the mobility of taste and aroma compounds in thickened systems. The diffusion coefficient of sucrose decreased when the thickness of tomato juices increased by the addition of tomato solids (2.6%) (Kokini *et al.* 1982).

In gelled model systems, the creation of a three-dimensional network may also affect aroma compounds diffusion. Rega *et al.* (2002) used the concentration profile method to measure the diffusion coefficients of methyl hexanoate, ethyl hexanoate, *trans*-2-hexenal and linalool in solutions of high methoxylated pectin at different concentrations. They observed a decrease of the diffusion coefficients due to the formation of a pectin network. In model fruit preparations, an increase of gel strength by addition of starch and carrageenans decreased the diffusion coefficient of ethyl butanoate measured by DOSY-NMR spectroscopy (Savary *et al.* 2006).

***In vivo mechanisms affecting texture – flavour interactions*:** Experimental conditions may affect the study of texture – flavour interactions. Variation in food model system viscosity may induce significant changes in the volume sampled by the panellists (Izutsu and Wani 1985) and thus affect flavour perception. Using a standard procedure set-up, Christensen (1977) observed a residual amount of the thicker solutions left in the cups. When experiment was reproduced using a volume controlled set-up (seringue), the impact of viscosity on saltiness perception was considerably reduced compared to the one observed with a standard procedure (cups).

As food is eaten, it is subject to changes in temperature, mechanical deformation, dilution and enzymatic breakdown due to saliva (Linforth and Taylor 2006). Substantial differences in flavour release might be expected between gelling agent types based on their different bulk properties. Guinard and Marty (1995) used the Time Intensity methodology and observed a higher maximum citrus (δ-limonene) intensity for starch gel compared to carrageenan and gelatin gels with comparable gel strength. Moreover, a decrease in aroma intensity with the increase of the concentration of hydrocolloids was observed for gelatin and carrageenan gels but not for starch. Those differences may be attributed to the behaviour of gels in the mouth as a function of their composition. Starch gels melt and release of the maximum intensity of aroma compounds very fast, compared to other gels that need to be broken down into small pieces. Differences in the in-mouth behaviour between starch and HPMC model systems may be explained by the capacity of starch samples to mix with saliva (Ferry *et al.* 2006) and its enzymatic breakdown by saliva (de Wijk *et al.* 2004). Variations in saliva composition not only affect texture perception, such as creamy mouth feel in custard dessert, but also affect aroma and taste perception such as vanilla flavour in custard dessert and sour flavour in mayonnaise (Engelen *et al.* 2007)

The textural properties of a food matrix may also have an impact on the way the product is broken down in the mouth. The role of mastication is to transform a food into a bolus ready for swallowing. When food texture changes, panellists do adapt their mastication process, which may affect flavour compounds release (Blissett *et al.* 2006). Wilson and Brown (1997) studied the impact of texture on gel breakdown and flavour perception. Eight panellists evaluated the commercial banana aroma intensity over time (Time Intensity methodology) for different gelatin gels (gelatin content: 5 to 25%). During the experiment, mastication patterns were recorded using electromyography. An increase in gels strength was found to increase the chewing time. The maximum perceived aroma intensity was lowered but the persistence was longer for firm gels compared to softer gels. Boland *et al.* (2006) studied the impact of gel firmness on the chewing behaviour and *in vivo* aroma release. Mastication time before swallowing was higher and the rate of aroma release was lower for firmer gels compared to softer gels. For non gelled systems, mastication is not required. Nevertheless oral movements were found to be dependant on texture for semi-solid model systems. Observation of oral processing by M-mode ultrasound imaging as a function of products properties showed that an increase in milk thickness induced an increase in oral movements and a longer processing in the mouth (de Wijk *et al.* 2006).

During ingestion, a food product is also subject to temperature changes (Delwiche 2004). An increase of product temperature may significantly affect the release of aroma compounds in the oral cavity. Heat transfer may be different as a function of food texture. In consumption conditions, Paçi Kora *et al.* (2004) observed an average increase of low fat yogurt temperature from 5 to 20°C. This evolution was found to be independent of the viscosity of yoghurt.

***The part of physico-chemical mechanisms in texture – flavour cross-modal interactions*:** The various physico-chemical mechanisms, related to the food matrices or their consumption in the mouth, may have an impact on taste and aroma compounds release, changing the quantity arriving near the receptors and thus taste and aroma perception. To go further in the insights of physico-chemical mechanisms involved in texture – flavour interactions, the strategy consists in quantifying flavour compounds closely to their own receptors and to link the data obtained on the release parameters for each flavour compound with data on flavour perception. Thus during this last decade, different methods have been developed to study the *in vivo* release of taste and aroma compounds.

Few studies in the literature aimed at quantifying the release of taste compounds as a function of food texture. In a hypothesis paper study, Jack *et al.* (1995) studied sodium chloride release during consumption of cheddar cheeses by a single panellist. Salt release was followed by conductivity measurement using an artificial dental palate containing electrodes. Relationships were observed between conductivity data and the sensory perception of cheddar texture. Chabanet *et al.* (2006) studied the impact of chicken sausage composition (fat, salt and dry extract reported to protein content) on salt release in the mouth and saltiness perception. Four participants were asked to chew a piece of sausage, to spit a sample of saliva and to evaluate saltiness for different periods. Saltiness perception was found to be highly dependant on sausage composition. From the PLS regression, this impact is related to the impact of food composition on salt release in saliva during eating. This kind of studies is applicable on solid products and remains not applicable to semi-solid products which present a short residence time in the mouth and a rapid mixing with saliva (Brossard *et al.* 2006). The difficulties of sampling as well as the absence of on-line sampling and analysis techniques are probably the reason of this lack of information dealing with the impact of texture on the release of taste compounds. Further developments are needed to measure the release of taste compounds in relation to taste perception.

Concerning aroma perception, several studies tried to relate texture - aroma interactions to *in vivo* release of aroma compounds. In recent years, new developments such as the Atmospheric Pressure Chemical Ionisation - Mass Spectrometry (APCI-MS (Taylor *et al.* 2000)) and the Proton Transfer Reaction - Mass Spectrometry (PTR-MS (Lindinger *et al.* 1998)) were used in order to measure the release of aroma compounds in a person's breath, while he or she eats a product.

Saint-Eve *et al.* (2006) observed a higher strawberry intensity for a low-viscosity yogurt than for high-viscosity yogurts. This result was in total agreement with a higher amount of aroma compounds released in the nasal cavity as measured by nose-space-APCI-MS. Using a free consumption protocol, Baek *et al.* (1999) and Boland *et al.* (2006) related aroma perception to the rate of release of aroma compounds in the nasal cavity, rather than to the total amount of aroma released. Nevertheless other authors failed into relating sensory data to aroma compounds parameters. For example, Hollowood *et al.* (2002) showed that an increase of HPMC amount induced a decrease in perceived strawberry intensity of solutions but did not affect *in vivo* aroma release as measured by APCI-MS. Similar results were observed for whey protein gels flavoured with diacetyl (Weel *et al.* 2002) and fruity model custard desserts (Lethuaut *et al.* 2004). Since aroma suppression by increased viscosity (or firmness) also occurs when the concentration of aroma compounds in the nasal cavity remains constant, those recent studies suggested that the observed texture – flavour interaction occurred at a central level (Weel *et al.* 2002). Moreover, as texture variation may also affect taste perception, some authors also suggested that the impact of texture on aroma perception is related to a taste – aroma interaction (Hollowood *et al.* 2002; Cook *et al.* 2003). More recently, Gierczynski *et al.* (2007) observed a strong impact of changes in the structure of model fresh cheese on *in vivo* aroma release. Those effects were not explained by *in vitro* structural modifications of the gel and consequently were attributed to an adaptation of food breakdown provided by the panellists to the texture of the product.

Cognitive mechanisms

The existence of cognitive mechanisms at the origin of texture – flavour interactions has been suggested in experiments where the impact of texture on perceived aroma intensity was studied using a protocol limitating physico-chemical mechanisms (Visschers *et al.* 2006; Bult *et al.* 2007). This new approach consisted in delivering texture stimulus in the mouth while odour (or aroma) stimulus was delivered ortho- or retro-nasally. In the experiment realised by Visschers *et al.* (2006), panellists were provided unflavoured water, custard dessert and protein gels and were asked to rate the strawberry aroma intensity delivered by an olfactometer. Tasting protocol and subsequent aroma delivery set-up were chosen in order to be representative of stimulation condition usually observed in the *in vivo* studies. Indeed, for semi-solid food products, aroma compounds are mainly released after swallowing (Buettner *et al.* 2001). Results revealed that perceived aroma intensity decreased when panellists ate semi-solid foods compared to water, but no significant differences were observed between the two gels presenting different firmness. The authors concluded to a cognitive texture – aroma interaction, but suggested that other factors such as the sweetness or the visual appearance of the tested samples may have influenced aroma perception. In the experiment realised by Bult *et al.* (2007), the stimuli of texture were not much different (0.07% fat milk thickened with í-carrageenan or unthickened) and visual cues were suppressed as 1 mL stimuli was delivered directly on the tip of the tongue using a system of membrane-liquid pumps. Participants rated the overall flavour intensity of the milk while a creamy aroma was delivered in the nasal cavity via an olfactometer. Results revealed that perceived flavour intensity decreased when milk viscosity increased, suggesting a cognitive origin of the texture – flavour interaction.

Integration of texture, aroma and taste inputs may explain the cognitive origin of texture – flavour interactions. In a neurological study, Cerf-Ducastel *et al.* (2001) investigated brain area activation by fMRI during consumption of pure chemical gustatory and lingual somatosensory stimuli. They observed a convergence of gustatory and lingual somatosensory inputs in the same cortical areas. In macaques, the representations of taste and texture (viscosity) inputs converge in the primary taste cortex and are combined with olfactory inputs in the orbitofrontal cortex (Rolls 2005). The convergence of the different modality inputs in the same cortical area might be the support of the proposed cognitive interactions between these modalities.

IMPACT OF FLAVOUR ON TEXTURE PERCEPTION

State of the art

Compared to texture – flavour interaction studies, few studies investigated the impact of taste or aroma changes on texture perception. One of the most famous papers is from Pangborn *et al.* (1973) concerning the influence of taste variation on perceived viscosity in the mouth. Solutions composed of five taste stimuli (sucrose, saccharine, citric acid, sodium chloride and caffeine) presented at four different concentrations have been thickened with HPC, CMC-L, CMC-M, sodium alginate and xanthan. Hydrocolloids were chosen in order to present various chemical characteristics and rheological properties. The perception of viscosity was highly dependant of the specific gum/taste combination. Sweetness variation had little effect on texture perception: the increase of sucrose content (2% to 8%) only induced an increase in perceived viscosity for xanthan solutions. Contrary to sucrose, perceived viscosity was reduced by the addition of other taste compounds (citric acid, sodium chloride, saccharin and caffeine).

In the case of the influence of aroma on texture perception, Pangborn and Szczesniak (1974) studied various aroma compounds and observed an impact of butanoic acid on the perceived viscosity of thickened solutions but no effect of acetaldehyde, acetophenone and dimethyl sulphide. In a real food product such as low fat stirred yogurts, Saint-Eve *et al.* (2004) observed an impact of olfactory quality of the flavouring agent on textural attributes. Yogurts with coconut and butter notes were judged to be thicker than those presenting green apple notes which were perceived as smoother. Contrary to these findings, some studies failed into finding any effect of aroma on texture perception. The addition of isoamyl acetate did not affect perceived thickness of custard dessert (Cayot *et al.* 1998) and gel firmness was not modified by the increase in strawberry concentration (0.7 to 1.4 $mL.Kg^{-1}$, Kälviäinen *et al.* 2000). As a conclusion, there are some evidence of an impact of taste and aroma compounds variation on textural, mainly thickness perception. Nevertheless, no general rules on the impact of flavour on texture perception can be driven from those examples. Results directly depend on the product as well as on the flavour components studied.

Mechanisms at the origin of flavour – texture cross-modal interactions

Physico-chemical mechanisms

Concerning the impact of taste on viscosity perception, Pangborn *et al.* (1973) aimed at understanding if the observed modifications in the perceived viscosity could be attributed to a modification of the structure by the addition of taste compounds. Viscosity measurements of tasted solutions were performed with a viscosimeter. The authors observed that differences in the perceived viscosity previously observed between solutions presented the same trend as instrumental viscosity evolution. Christensen (1980b) observed that the perceived viscosity of CMC solutions slightly increased with sucrose and decreased in the presence of sodium chloride and citric acid. These differences in judgements of perceived viscosity have been attributed to the alteration in the Newtonian behaviour (rheological properties) of the thickened solutions produced by the addition of taste substances. Concerning the impact of aroma on texture perception, Pangborn and Szczesniak (1974) related the changes in perceived viscosity induced by butanoic acid to changes in rheological behaviour. Finally, Paçi Kora *et al.* (2003) observed that the differences in perceived thickness between yogurts presenting different amounts of fruity flavouring agent were also perceived without aroma stimulus (panellists wore nose clips), but with a smaller amplitude.

Flavour may also affect the destruction of food products in the mouth. Indeed, de Wijk *et al.* (2006) used M-mode ultrasound imaging and observed that food's sweetness affected oral movements especially during the bulk phase. Other authors also hypothesized that aroma – texture interaction may be due to a cognitive mechanism and that panellists may adopt different chewing behaviour when the aroma of the product was modified (Saint Eve *et al.* 2004).

Cognitive mechanisms

Some authors suggest that the impact of taste and aroma stimuli on texture perception may be due to cognitive mechanisms (Christensen 1977; Saint-Eve *et al.* 2004). This hypothesis sounds realistic as textural, taste and olfactory inputs converge in the same cortical area (Rolls 2005). To better understand if flavour – texture interactions are attributed to cognitive rather than physico-chemical mechanisms, some authors developed model systems presenting different tastes but the same rheological properties. Burns and Noble (1985) separated the effect of sweetness and instrumental viscosity of sucrose on the sensory properties of different vermouths varying in sucrose concentrations but with the same viscosity. Viscosity was kept constant by substituting sucrose by the nonsweet Polycose®. At identical viscosity, the vermouths with high sucrose concentration were judged to be more viscous than vermouths with low concentrations in sucrose. Others authors choose a similar approach but failed into showing any impact of the variation in tastant composition on texture perception. In orange flavoured gellan gels, Damásio *et al.* (1997) compensated rheological changes due to sucrose addition by using gellan/xanthan/ locust bean gums mixtures. At identical mechanical properties (determined by uniaxial compression measurements), sweetness variation did not affect firmness, rigidity and hardness perception. Concerning aroma, Lethuaut (2004) verified that fruity blend concentration (4.5, 18 and 72 mg.Kg^{-1}) did not affect rheological properties (penetrometry) of custard desserts. In this condition aroma intensity was found to punctually affect the perceived texture properties such as springiness and unctuousness but had no impact on the evaluation of firmness, brittleness and smoothness attributes. Finally, in our study on flavour – texture interactions, consumers tasted custard desserts presenting two levels of sweetness (to keep viscosity constant, half of sucrose was replaced by lactose) with and without wearing nose-clips. Results showed that neither sweetness intensity nor aroma perception did have any impact on consumer thickness perception (Tournier 2006).

As a conclusion, few studies have investigated the impact of taste and aroma on the textural properties of a food product. Some of the observed flavour – texture interactions were attributed to a modification of the rheological properties or to different mastication patterns. Other studies hypothesized the existence of cognitive mechanisms but this hypothesis needs to be more deeply investigated.

TASTE – AROMA CROSS-MODAL INTERACTIONS

State of the art

Taste – aroma interactions have received a great interest this last decade, especially by psychologist researchers (Prescott 2004a; Valentin *et al.* 2006). These studies generally consisted in presenting to the participants a stimulus composed of taste and/or olfactory compounds and in comparing the scores obtained for samples composed of only one stimulus with scores of solutions composed of both stimuli.

Numerous studies investigated the impact of olfactory stimulus on taste perception. **Table 1** presents some aroma – taste interactions observed in the literature. The impact of olfactory stimuli on taste perception is interpreted in terms of taste enhancement (the so-called 'odour-induced taste enhancement' appeared when taste intensity of the mixture was higher than taste intensity of taste compound alone) and taste suppression (taste intensity of the mixture is lower than the intensity of each taste solution). Most of the studies were focused on sweetness perception (Valentin *et al.* 2006). Results showed that the impact of aroma on taste perception depends on the nature of aroma (**Table 1**). Some aroma notes such as strawberry, caramel, maracujá and vanilla enhance perceived sweetness whereas others have no effect (wintergreen, eucalyptol, ham) or even decrease sweetness perception (chocolate, damascene and angelica oil). Studies presented in **Table 1** mainly dealt with model solutions and few of them investigated aroma – taste interaction in a real food product. As an example, in a cocoa drink, Labbe *et al.* (2006) observed an enhancement of bitterness induced by the cocoa aroma and an increase in sweetness by vanilla aroma. This study, as well as those presented in **Table 1**, suggests that aroma – taste interactions mainly depend on the nature of the aroma and taste compounds used.

Contrary to previous studies, the impact of taste on aroma perception received less attention. Kuo *et al.* (1993) studied the impact of sucrose, citric acid and sodium chloride on citral and vanilla perceived intensities and observed that the main effects were the increase of citral intensity with the addition of citric acid, the increase in vanilla intensity by sucrose addition and the decrease in vanilla intensity by citric acid and sodium chloride addition. von Sydow *et*

Table 1 Examples of aroma → taste interactions.

Aroma/ Odour	taste	Effect	Products	Authors
Almond	Sweet	+	MS	Frank *et al.* 1993
Caramel	Sweet	+	MS	Stevenson *et al.* 1999
Cocoa	Bitter	+	Chocolate beverage	Labbe *et al.* 2006
Garlic	Salty	+	Thickened MS	Cook *et al.* 2003
Green apple	Sour	+	Yoghurts	Saint-Eve *et al.* 2004
Lemon	Sour	+	MS	Nguyen 2000
	Sweet	+	MS	Frank *et al.* 1993; Schifferstein and Verlegh 1996; Nguyen 2000
Maracujá	Sweet	+	MS	Stevenson *et al.* 1999
Peach	Sweet	+	MS	Cliff and Noble 1990
Strawberry	Sweet	+	MS, whip cream, yoghurts	Frank and Byram 1988; Frank *et al.* 1989, 1993; Schifferstein and Verlegh 1996; Stevenson *et al.* 1999; Saint-Eve *et al.* 2004
Vanilla	Bitter	+	Caffeine milk	Labbe *et al.* 2006
	Sour	+	MS	Nguyen 2000
	Sweet	+	MS, chocolate beverage	Clark and Lawless 1994; Nguyen 2000; Labbe *et al.* 2006
Chocolate	Sour	0	MS	Cayeux and Mercier 2003
Eucalyptol	Sweet	0	MS	Stevenson *et al.* 1999
Ham	Sweet	0	MS	Schifferstein and Verlegh 1996
Lemon	Sour	0	MS	Cayeux and Mercier 2003
Peanuts	Sweet	0	Whipped cream	Frank and Byram 1988
Strawberry	Salty	0	MS	Frank and Byram 1988
Vanilla	Sour	0	MS	Cayeux and Mercier 2003
Vanilla	Sweet	0	Caffeine milk	Labbe *et al.* 2006
Wintergreen	Sucrée	0	MS	Frank *et al.* 1993
Angélica	Sweet	-	MS	Stevenson *et al.* 1999
Chocolate	Sweet	-	MS	Frank *et al.* 1993
Damascone	Sweet	-	MS	Stevenson *et al.* 1999
Maltol	Sweet	-	MS	Stevenson *et al.* 1999

MS: model solution, +: odour-induced taste enhancement, -: odour-induced taste suppression, 0: no effect *al.* (1974) examined the impact of sucrose level on taste and aroma perception of blueberry and cranberry juices. Additional sucrose was found to increase fruity, floral and fragrant notes and to decrease vinegar, resinous and green notes. Other authors observed an impact of taste intensity on aroma perception. Increase in sucrose concentration was found to increase aroma intensity of orange sherbets (Stampanoni 1993) as well as dynamic fruitiness intensity and duration of orange-flavoured solutions (Bonnans and Noble 1993). In custard desserts, fruity aroma intensity only increased when sucrose concentration increased from 2.5 to 5%, but was not further modified by higher sucrose concentration (5 to 10%) (Lethuaut *et al.* 2005). Finally, in another study, fruitiness of strawberry and orange solutions was not modified by sucrose addition but was affected by aspartame for low concentrations in aroma (0.4 and 0.6% for orange aroma and 0.6 and 0.9% for strawberry aroma) (Wiseman and McDaniel 1991). As observed for aroma – taste interactions, taste – aroma interactions are dependant of the couple taste/aroma compounds used.

Mechanisms at the origin of taste – aroma cross-modal interactions

Physico-chemical mechanisms

Physico-chemical mechanisms might explain the impact of taste on aroma perception. In a general manner, the volatility of aroma compounds increased with the presence of salt in the media which can be explained by a 'salting out' phenomenon, which has been extensively reviewed by Salles (2006). Apart from salt, other organic molecules are able to modify the volatility of aroma compounds, such as sweeteners (Nahon *et al.* 1998), wine polyphenols (Dufour and Bayonove 1999), ethanol (Conner *et al.* 1998).

In the case of sweetness – aroma interactions, there are some evidences that the concentration of sucrose in model systems may affect aroma compounds release. However, some contradictory results were observed. Friel *et al.* (2000) determined the concentration at the equilibrium, of 40 aroma compounds in the headspace above an aqueous sucrose solution (0 to 65% w/v). As sucrose concentration increased, the measured concentration either increased or was not affected or decreased, depending on aroma compounds. Differences among aroma compounds may be explained by their volatility (Delarue and Giampaoli 2006) as reflected by their GC/FID retention times (Nahon *et al.* 1998). The increase in aroma release when the amount of sucrose increased was attributed to a 'salting out' effect (Voilley *et al.* 1977; Hansson *et al.* 2001; Lubbers *et al.* 2003). This effect was attributed to a decrease of free water because of disaccharide hydratation which induced a decrease in aroma compound solubility and thus an increase in release. Decrease of aroma compounds release may be attributed to the increase of viscosity induced by sucrose addition (Savary *et al.* 2006). Nevertheless in solutions thickened with sucrose or CMC adjusted to a comparable viscosity, differences observed for in-mouth aroma release could also be explained by steric hindrance and/or molecular interactions between sucrose and non polar aroma compounds (Roberts *et al.* 1996).

Such physico-chemical mechanisms may affect aroma compounds release and thus aroma perception. Nevertheless, attention has to be paid as sucrose concentration (60%) used in the previous studies are much more important than those used to study taste – aroma cross-modal interactions. Some authors aimed at quantifying aroma release close to the receptors and at linking aroma compounds release parameters with aroma perception. In CMC model system, Hollowood *et al.* (2002) observed an increase in benzaldehyde intensity when sucrose content increased (25 to 80 $g.Kg^{-1}$). Nevertheless, APCI-MS measurements showed that aroma release remained the same for all sucrose contents. Other authors observed an increase in perceived fruitiness for sucrose/acid solutions and custard desserts with an increase in sucrose content, that could not be related to changes in aroma release (Lethuaut *et al.* 2005; Pfeiffer *et al.* 2006). These results suggest that taste – aroma interactions could not be only attributed to physico-chemical mechanisms. This hypothesis is in agreement with the results obtained by Davidson *et al.* (1999). By combining sensory evaluation (Time Intensity) and *in vivo* measurements they showed that perceived mint intensity was more related to sucrose release during consumption than to menthone release.

Cognitive mechanisms

In most of the studies reported in **Table 1**, interactions have been studied using ratings on scales. Nevertheless, some authors observed that taste – aroma interactions may be dependant on the rating instructions provided to the participants. For example, Frank *et al.* (1993) found that the impact of aroma on taste perception is dependant of the responses alternatives. When participants rated the sweetness of a sucrose/strawberry aroma solution, an odour-induced taste enhancement was observed (the mixture was rated sweeter than the unflavoured sucrose solution). Nevertheless, when they were provided several scales (sweetness, sourness and fruitiness scales), this enhancement was not observed any more. As this effect depends on response alternatives provided by the experimenter, some authors attributed this odour-induced taste enhancement to response biases which they called the 'dumping' effect (Clark and Lawless 1994). This dumping effect corresponds to a general tendency of participants, who are not provided with the appropriate scale, to 'dump' their sensation(s) on the only available scale(s) (Clark and Lawless 1994). van der Klaauw and Frank (1996) investigated if the effect observed by Frank *et al.* (1993) was more related to the number of scales or to the attribute(s) proposed. Participants were provided a sucrose solution and a sucrose/strawberry solution. Strawberry solutions were evaluated using 6 conditions in which the number of scales and the attributes varied. Over the different conditions, odour-induced taste enhancements were observed when participants rated only the taste (sweetness) but disappeared when the sweetness and the fruity attributes were evaluated together.

For other authors, aroma impact on taste perception can be attributed to a central integration (Prescott *et al.* 2004b). Indeed, some studies could not be explained only in term of responses biases. The most relevant example is the study from Dalton *et al.* (2000) where taste – aroma interaction was investigated without using rating scales but by measuring detection threshold. The authors used sub-threshold levels of a tastant (saccharin) and an odour (benzaldehyde), and hypothesized that the taste – aroma interactions should make the sub-threshold combination perceptible by the participants. They observed that the detection threshold for benzaldehyde, delivered orthonasally via sniffing, was lower when panellists held a sub-threshold solution of saccharin in their mouths compared to a water solution. This effect was not observed when the sweet solution was replaced by an umami (Monosodium glutamate) solution. This taste – aroma interaction has been later confirmed by Pfeiffer *et al.* (2005) for 12 participants among 16. Moreover, the authors also demonstrated that taste and aroma interact only when both stimuli are presented simultaneously. Furthermore, even when other studies were conducted using ratings scale, the results suggested that taste-aroma interactions could not be only explained by response biases. For example, Frank and Byram (1988) proposed the same number of scales to the participants and observed an odour-induced sweetness enhancement of whip cream for a strawberry aroma but not for a peanuts butter aroma. To understand the respective part of the dumping effect in the interactions, Valentin *et al.* (2006) asked participants to evaluate the sourness intensity of sour solutions flavoured either with vanilla or with lemon aroma. They observed an odour-induced enhancement of sour perception for both aroma, when participants rated sourness only. When participants were asked to rate taste and aroma intensities simultaneously, the enhancement effect was reduced for lemon aroma and disappeared for vanilla aroma. This study suggests that providing appropriate rating scales to participants suppress the effect due to response biases but does not suppress totally the interactions between taste and aroma. These experiments also highlighted that taste – aroma interactions depend on the association between both stimuli. In literature, several tools have been proposed for measuring the association between taste and aroma association: the congruency, the similarity, the 'smell taste of the odorants'. In Schifferstein and Verlegh (1996), participants were asked to rate the congruency of three sucrose/odorant mixtures: sweet taste in combination with strawberry, lemon or ham aroma. Odour-induced taste enhancement was only found for the congruent mixtures (strawberry/sweetness and lemon/sweetness). Nevertheless, the authors did not found any linear relationship between the degree of congruency and the intensity of the enhancement effect. Frank *et al.* (1991) asked the participants to evaluate the similarity of mixtures of tastes (sweetness, saltiness, sourness and bitterness) and aroma (almond, chocolate, lemon, peanuts, strawberry and wintergreen). Similarity between taste and aroma was found to be a good predictor of the impact of aroma on taste perception, except for quinine. Finally, Stevenson *et al.* (1999) showed that the 'smell taste of the odorant (evaluated by sniffing)' allowed to evaluate the impact of strawberry, caramel and maracujá aroma on sweetness perception. Nguyen (2000) compared congruency, similarity and the 'taste of odour' for different mixtures: vanilla/sourness, vanilla/sweetness, lemon/sourness and lemon/sweetness. Contrast tests showed that only the similarity and the 'taste of smell' allowed to predict the impact of aroma on taste perception.

The interactions between taste and aroma depend on taste – aroma association and this association may come from their common presence (co-occurrence) in food eaten by consumers (Frank and Byram 1988). Stevenson *et al.* (1995) showed that prolonged exposure to a taste/aroma mixture can modify the 'smell taste of the odorant'. In their studies, Stevenson *et al.* (1995) exposed participants to solutions composed of a relatively new aroma (lychee and water chestnut) in mixture with sweet (sucrose) and sour (citric acid) taste. They clearly showed that the lychee and water chestnut smell were rated as significantly 'sweeter' or 'sourer', depending on the taste they were combined with during the exposition. They also showed that when an odour was associated with one taste (sweetness), it was rated as less intense for the other tastes (sourness). The learning effect has also been highlighted when taste was evaluated on a scale. For instance Prescott (1999) proved that aroma notes which initially did not affect sweetness perception, induced a taste-enhancement after a learning phase in which participants were exposed to these aroma in solution with sucrose.

The interactions between taste and aroma depend on a central integration of both stimuli which depend on individual food experience. Thus, consumers who tasted sweetened yoghurts flavoured with strawberry during their life would associate strawberry aroma to sweet taste. The corollary of this learning is that persons who live in different environments will have different food experience, which may modify the interactions between taste and aroma. King *et al.* (2007) observed differences in retronasal odor intensities for several descriptors while profiling beverages in which Brix and acidity were varied and attributed these effects to cognitive associations due to the panel's extensive prior experience in profiling commercial samples. For example increasing Brix from 8 to 12 or decreasing acidity from 0.3 to 0.2 significantly increased scores for fruity and significantly decreased scores for gree. On the other hand they found no evidence for gustatory sweetness enhancement when the flavour had an orthonasal "sweet" odour, such as the banana flavour or the green apple flavour. Moreover, Sauvageot *et al.* (2000) observed that taste – aroma interactions was culture dependant. The interaction between sweet taste and strawberry aroma was found to be stronger for American people compared to French people. To test this hypothesis, they asked French and American participants to cite all the words that come to their mind when they read the word "strawberry" (free association task). Results showed that only 9% of French persons spontaneously associated "strawberry" and "sweet" compared to 24% of American persons.

Neurophysiological studies have shown a convergence of gustatory and olfactory inputs in the same cortical area that may be the support of cognitive interactions between these modalities. In primates, Rolls and collaborators studies showed that among 112 neurons in the orbitofrontal cortex, 68% were unimodal neurons (34% only respond to gustatory stimuli and 13% only to olfactory stimuli) and 32% were multi-modal (13% respond to olfactory and gustatory stimuli (Rolls 2005)). These different kinds of neurons are generally close to each other and may be formed from unimodal neurons. Moreover, the response of olfactory neurons in the orbitofrontal cortex may be modified by the taste with which odour has been associated (Rolls 2002).

CONCLUSION

This review has considered the interactions between taste, aroma and texture as well as the possible mechanisms surrounding these interactions. Those mechanisms can be from physico-chemical and cognitive origins. Lots of examples have been presented. Even if in the case of taste – aroma interactions mechanisms are now identified, real mechanisms at the origin of the impact of texture on flavour perception are still not fully revealed. Diversity of these mechanisms is probably the reason why understanding the interactions is so challenging. All the proposed examples highlight the importance of adopting a multidisciplinary approach to study the interactions, especially when physicochemical mechanisms can greatly affect perception. Principally integrating sensory, physicochemical and psychological approaches of interactions revealed to be a challenging and promising scientific building. For example, because texture – flavour interactions deal with physico-chemistry, studies have mainly been conducted with trained panellists. For the future, studying these interactions from a consumer point of view seems necessary to understand the application of interactions knowledge to food products. Moreover cognitive mechanisms behind texture – flavour interactions need to be more investigated for example by using a psychological approach.

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