Tasty sounds:
Crossmodal associations between chemosensory and auditory stimuli

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Short abstract

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The sensory evaluation of food products prior to and during ingestion is a vital process. As such, it is influenced by a variety of factors, comprising both contextual cues and sensory features of the food. The research presented in this thesis was designed to explore the crossmodal associations between auditory (musical notes) and chemosensory stimuli. The reported experiments revolve around three main goals. The first goal was to demonstrate the existence of reliable crossmodal associations between auditory and chemosensory stimuli. To this end, both implicit and explicit tasks were used. Specific pairings of basic tastes, flavours, and odours with musical notes were shown to be preferred, both in term of the pitch of the note and its timbre. The second goal was to suggest potential mechanisms or factors underlying these crossmodal associations. Two such factors were studied: familiarity and pleasantness. The familiarity with the chemosensory stimuli appeared not to affect much the crossmodal associations with musical notes. The pleasantness of the chemosensory stimuli was a main factor in the associations with the timbre of the note, but failed to satisfactorily explain the associations with the pitch of the note. Finally, the third goal was to evaluate the influence the congruence of auditory stimuli might have on the perception of simultaneously-presented chemosensory stimuli. Background soundtracks were shown to influence ratings of a food item on the bitter-sweet continuum. No such effect was observed when musical notes were presented simultaneously with odours. The research reported in this thesis constitutes the first detailed account of crossmodal associations between musical notes and a variety of chemosensory stimuli. The level at which such crossmodal associations might happen, as well as potential applications, are discussed, as well as possible directions for further research on the topic.

Extended abstract

The evaluation of food before consumption is vital to ensuring that we get the necessary nutrients while avoiding poisons. It is thus not surprising that we have evolved to use a variety of sources of information in order to decide whether to eat or drink something or not: not only the sensory features of the food in front of us, but also knowledge from previous encounters with the food, as well as contextual cues. For example, factors as various as the ambient lighting, the decoration, or the background music playing in a restaurant have been shown to affect people's behaviour towards food and drink. Effects have been documented on such things as people's choices, the quantity ordered, the time taken to finish their meal, or the money spent (Bell, Meiselman, Pierson, & Reeve, 1994; Caldwell & Hibbert, 2002; Milliman, 1986; North, Shilcock, & Hargreaves, 2003; Oberfeld, Hecht, Allendorf, & Wickelmaier, 2009).

Food is central to our experience of the world. We tend to use vocabulary related to taste metaphorically to describe seemingly unrelated concepts, such as personality (e.g., a sweet person) or morality (physical and moral disgust elicit very similar responses and the same vocabulary is used for both; see, e.g., Chapman, Kim, Susskind, & Anderson, 2009). In music, the Italian word *dolce* is commonly used to indicate that the music should be played gently and sweetly. Conversely, musical vocabulary is used when the components of a perfume are described as *notes*.

Despite these connections, research on crossmodal associations between chemosensory and musical features is scarce. Most studies have compared the effect of different types of music, tempos, or volumes on food-related behaviours. Moreover, these behaviours are most often measured in terms of choices, quantity of food consumed, time or money spent in a store or restaurant, rather than on sensory features of the food.

The present thesis thus explores the crossmodal associations that exist between chemosensory stimuli and musical notes. The research was organised around three main goals: First, to demonstrate the existence of these crossmodal associations, as well as to describe

them for a variety of chemosensory stimuli; Second, to suggest mechanisms for these crossmodal associations; Third, to study the influence auditory stimuli might have on the evaluation of chemosensory stimuli resented simultaneously.

Chapter 1 starts with a brief overview of multisensory perception, focusing on crossmodal associations and metaphors (Section 1.1). General information on taste and olfaction is provided in Section 1.2. The various ways of classifying tastes and odours are reviewed. A description of how several sensory modalities combine to give rise to the perception of flavour is provided. The crossmodal associations that have been reported between either taste or olfaction and a variety of other sensory modalities are listed. Finally, the role of expectations, hedonic value, and familiarity in chemosensory perception is discussed. Section 1.3 explores the emotions and concepts that can be conveyed by music, as well as the various crossmodal associations that exist with pitch. Finally, Section 1.4 reviews the various ways in which chemosensory and auditory perception interact. The influence on chemosensory perception of the sounds made by the consumption of food, as well as of the background music or noise is reviewed. Cases of synaesthesia involving the chemical senses are described, as well as previously reported crossmodal associations between the chemical senses and sounds.

Chapter 2 reports two experiments that used implicit tasks to demonstrate the existence of crossmodal associations between basic tastes and pitch. In Experiment 2.1, a version of the implicit association test (IAT) was used to assess the strength of the association between high-pitched sounds and names of sour-tasting or sweet-tasting foodstuffs, and between low-pitched sounds and names of bitter-tasting or salty-tasting foodstuffs. This test is based on the use of the same response key for two categories of stimuli. If the two categories are associated, it renders the task easier and leads to better performance (measured through reaction times and error rates). The results of Part 1 demonstrated that the association of sourness with high pitch and bitterness with low pitch was preferred over the reverse combination (sourness with low pitch and bitterness with high pitch). Part 2 similarly demonstrated the existence of a

preference for associating sweetness with high pitch and saltiness with low pitch. A similar task, the go/no-go association task (GNAT), was used in Experiment 2.2 to evaluate the relative strengths of these associations. Analysis of the sensitivity of participants' responses suggested that both sour- and sweet-tasting (names of) food items were associated with high-pitched sounds, while showing no evidence of any association of bitterness or saltiness with low-pitched sounds.

The experiments reported in Chapter 3 were designed to confirm these results using a variety of chemosensory stimuli: solutions of basic tastes and flavours (Experiment 3.1), flavoured milk solutions (Experiment 3.2), crisps (Experiment 3.3), and wine-related odours (Experiment 3.4). In this series of experiments, an explicit task was used: That is, the participants selected a musical note to associate with a chemosensory stimulus. Musical notes played by four types of musical instruments at 13 pitches were used as auditory stimuli. Ratings for a variety of features of the chemosensory stimuli were obtained in order to uncover possible factors underlying the crossmodal associations. The association of sweet and sour tastes to high-pitched notes was confirmed. Fruity flavours and odours were also associated with high-pitched notes. By contrast, umami and bitter tastes were preferentially matched to low-pitched notes, as well as woody or smoky odours. The choice of musical instrument seems to have been driven primarily by a matching of the hedonic value of both types of stimuli. Principal component analyses (PCAs) consistently found pleasantness as a factor underlying the ratings of the stimuli. Other factors that appeared less consistently included familiarity, complexity and intensity.

Based on the results of the experiments reported in Chapter 3, Chapter 4 studied in more details the role of familiarity and pleasantness in the crossmodal associations between chemosensory stimuli and musical notes. Using the same experimental design as Experiment 3.4, Experiment 4.1 presented wine-related odours and compared the associations made by regular wine tasters compared to a control group. No significant effects of familiarity were

found. Experiment 4.2 examined the role of pleasantness by presenting three types of chocolate (milk, dark, and marzipan-filled). The dark chocolate was selected for further analysis as it elicited a wide range of pleasantness ratings. The results revealed that when considering a single stimulus (dark chocolate), pleasantness affected the associations made with musical instruments, but not those made with pitch.

The experiments reported in Chapter 5 focused on investigating the influence that auditory stimuli might have on chemosensory perception based on their perceived congruency. In Experiment 5.1, participants tasted pieces of cinder toffee, which is both bitter and sweet. At the same time, they listened to a soundtrack designed to correspond crossmodally with either bitterness or sweetness. The toffee was rated as significantly sweeter when participants listened to the "sweet" soundtrack than when they listened to the "bitter" soundtrack. In Experiment 5.2, high- or low-pitched musical notes (or white noise) were presented at the same time as odours. While there was an effect of the presentation of a musical note on odour intensity ratings, no specific effects on bitterness or sourness ratings were found. The differences between the two experiments that might have led to these seemingly contradictory results are discussed.

Finally, Chapter 6 summarises the main findings. The theoretical implications of these findings are discussed, in particular the possible mechanisms underlying the crossmodal associations. An important role of emotions in mediating the crossmodal associations documented here is suggested. Potential practical applications for these findings in a variety of contexts (marketing, restaurants, art, and nutrition) are also discussed. Moreover, directions for further studies on the topic are suggested: Experiments focused on the role of emotions might lead to valuable insights on the mechanisms underlying the crossmodal associations. Cross-cultural or developmental studies might also provide useful information in better understanding the origins of these crossmodal associations.

1 Chapter 1: Introduction

1.1 Multisensory perception

1.1.1 Dealing with a multisensory world

The senses have traditionally been studied separately, with a focus on the visual and auditory modalities. However, in everyday life, they rarely, if ever, work in isolation. For example, when going to a restaurant, the overall experience of the meal will be affected not only by the taste of the food, but also by its smell, its texture, how it is arranged on the plate, the level of the background noise or music, and a number of other factors.

It is thus not surprising that our brains have evolved to deal with multisensory inputs. There is more and more evidence to suggest that the feedback pathways from multisensory to unisensory areas play an important role and that perception in one modality can affect the perception of stimuli in another modality (Driver & Spence, 2000; Shams, Wozny, Kim, & Seitz, 2011). It has even been suggested that most of the cortical areas traditionally thought of as unisensory are, in fact, multisensory (Ghazanfar & Schroeder, 2006). Multisensory interactions have indeed been shown to modulate unisensory responses even at the primary cortical level (Schroeder & Foxe, 2005). Audition and, to some extent, olfaction can be used in action planning, and interact crossmodally with vision when making grasping movements (Aglioti & Pazzaglia, 2011; Castiello, Zucco, Parma, Ansuini, & Tirindelli, 2006; Parma, Ghirardello, Tirindelli, & Castiello, 2010). Viewing pictures of food can activate the gustatory system (Simmons, Martin, & Barsalou, 2005). Multisensory interactions between all sensory modalities are thus much more prevalent than previously thought (see Calvert, Spence, & Stein, 2004; Driver & Noesselt, 2008, for reviews).

Early theories of how the sensory modalities interact suggested that one sense dominated the others. Experimental evidence indicated that in many cases, vision seemed to

dominate (e.g., Hecht & Reiner, 2009; Posner, Nissen, & Klein, 1976; Spence, Shore, & Klein, 2001), while in a few exceptions audition dominated (Burr, Banks, & Morrone, 2009; Shams, Kamitani, & Shimojo, 2000; Welch, DuttonHurt, & Warren, 1986). These observations led to several hypotheses attempting to explain which modality would dominate in a particular situation, such as modality precision, directed attention or modality appropriateness (Welch & Warren, 1980). Later models, such as maximum-likelihood estimation (MLE; Ernst & Banks, 2002), detailed how information from different modalities was integrated, in order to provide the best estimate of an event. According to the Bayesian coding hypothesis, information from the senses is represented and propagated in the form of conditional density functions. The final percept would then be a combination not only of the likelihood functions from different modalities (as in MLE), but also of a prior density function representing the a priori probability of the event (Ernst & Bülthoff, 2004; Knill & Pouget, 2004).

1.1.2 Metaphors and crossmodal associations[1]

Metaphors are defined as "an implied comparison between two things of unlike nature that yet have something in common" (Corbett, 1990, p. 144). Focusing on the "unlike nature" of the two things suggests that metaphors are a kind of confusion, and thus might best be avoided for the sake of clarity. However, the "something" they have in common might be seen as a way to multiply the perspectives on a given object or situation, and thus be a way to generate insights (see Cazeaux, 2002, for a review). Following Lakoff and Johnson's (1980) book, *Metaphors we live by*, there has been growing research interest in studying metaphors, as a way to better understand cognition. Metaphors are pervasive in everyday language. It has been suggested that they are constructed from basic metaphors (categorised as perceptual-perceptual, crossmodal, movement-movement, and perceptual affective) that are "pre-wired"

[1] In the present thesis, the term crossmodal association has been chosen, following Harrison's suggestion (Harrison, 2001, p.35), in order to avoid any confusion with the experience of synaesthetes. Note, however, that a number of other terms are used in the literature to describe the same phenomenon (e.g., synaesthetic associations, synaesthetic correspondences, or crossmodal correspondences).

and appear very early in infants (Seitz, 2005). These basic metaphors would constitute a basis for the construction of other metaphors, which would also be influenced by culture and language. Metaphors have been shown to activate embodied representations. Santana and de Vega (2011) demonstrated that speeded upward hand motions were faster when participants were reading sentences that contained metaphors implying an upward movement (e.g., she climbed up in the company) than when they were reading metaphors implying a downward movement (e.g., he fell into depression). Moreover, even sentences suggesting these metaphors without using a verb implying motion (e.g., she succeeded as a professional) led to the same effect. Metaphors can also greatly influence how we reason about social issues. Thibodeau and Boroditsky (2011) demonstrated that when crime was described to participants as a virus, they suggested very different solutions (more prevention and less punishment) for decreasing crime rate than in a condition where crime was described as a beast. Even a single use of the word *virus* versus *beast* was sufficient to elicit the effect. Moreover, participants were unaware of the influential aspect of the metaphors in their decision. Metaphors can thus affect both our motor and cognitive processes, and the way we use them seem to reflect both innate and cultural conceptions of the world.

In parallel to studies on metaphors, many crossmodal associations have also been reported. Crossmodal associations differ from metaphors in that they are not necessarily commonly used in language. However, they make sense to most people, at least those having the same cultural background. Von Hornbostel (1931) was one of the first to study the phenomenon. He suggested that brightness was an amodal dimension that could be applied not only to levels of grey, but also to sounds, pain or odours, among others. He tried to explain the ordering of odours on the bright-dark dimension through their chemical composition. Marks (1982) studied how participants rated novel audio-visual metaphors, such as “loud moonlight” or “golden trumpet note”, in terms of their loudness and brightness. He concluded that greater brightness corresponded to greater loudness and higher pitch (see also Schiller, 1935). More

recently, crossmodal associations between a variety of modalities have been reported: odours and tactile sensations (Churchill, Meyners, Griffiths, & Bailey, 2009; Demattè, Sanabria, Sugarman, & Spence, 2006), pitch and size (Evans & Treisman, 2010; Gallace & Spence, 2006), or odours and colours (Demattè, Sanabria, & Spence, 2006; Gilbert, Martin, & Kemp, 1996), to name but a few (see also Spence, 2011a, for a review, and Sections 1.2.4, 1.3.3, and 1.4.4 in the present chapter).

To date, three categories of crossmodal associations have been proposed, based on their origin (Schifferstein & Tanudjaja, 2004; Spence, 2011a): innate, statistical, and semantically-mediated. Innate associations reflect the organisation of the perceptual system. Statistical associations between perceptual dimensions that often co-occur in the environment are picked up through perceptual learning. Finally, semantically-mediated associations occur when common linguistic terms are used to describe stimuli along different dimensions.

According to the semantic coding hypothesis, crossmodal associations occur at an amodal level, where the information is already in a semantic format, even when the origin of the association might be innate or statistical (Martino & Marks, 1999, 2000). However, the bases on which the associations are formed remain largely unexplained. One attempt to describe the use of one dimension in several perceptual systems is Walsh's (2003) theory of magnitude (ATOM), which proposes that time, space, and quantity are part of a generalised magnitude system, which would explain the numerous interactions between these systems. With his semantic differential scaling method, Osgood (1952) came to the conclusion that all stimuli could be described based on three factors: evaluation (good-bad), activity (active-passive), and potency (strong-weak; see also Osgood, Suci, & Tannenbaum, 1957). Crossmodal associations could thus result from a matching of stimuli based on these three factors. Interestingly, these three factors can also be used to describe emotions (Russell & Mehrabian, 1977). This three-factor model could thus also potentially explain associations between visual or auditory stimuli and emotions

(Collier, 1996). Alternatively, the matching of stimuli could be mediated by the emotions they elicit (Schifferstein & Tanudjaja, 2004).

1.2 Gustation and olfaction

1.2.1 Basic tastes

Taste sensations are traditionally described by four basic tastes: bitter, salty, sour, and sweet. Following this approach, it is assumed that all tastes can be described in terms of the relative contribution of each basic taste. The idea was formalised by Henning (1916), who proposed a model in which taste space was represented as a tetrahedron, with each basic taste at a corner. It has even been suggested that these basic tastes should be considered as separate submodalities of taste (McBurney & Gent, 1979). A fifth taste, umami, was first described in 1909 by a Japanese chemist, Kikunae Ikeda. However, umami has only started to become widely recognised as a basic taste at the end of the 20th century (Ikeda, 2002; Kurihara, 2009; Lindemann, Ogiwara, & Ninomiya, 2002). More recently, other basic tastes (i.e. that can be perceived, but cannot be described in terms of existing basic tastes) have been proposed: fatty acids (Chalé-Rush, Burgess, & Mattes, 2007; Fukuwatari et al., 1997; Laugerette, Gaillard, Passilly-Degrace, Niot, & Besnard, 2007; Mattes, 2009), calcium (McCaughey & Tordoff, 2011), water (Di Lorenzo & Rosen, 2011), metallic (Stevens, Smith, & Lawless, 2006). However, the very concept of a basic taste is ill-defined (Delwiche, 1996; Erickson, 2008), and the use of labels referring to basic tastes might underestimate the number of categories actually present when sorting stimuli (Ishii & O'Mahony, 1987). Moreover, the use of the four basic tastes to describe stimuli might not necessarily be appropriate, as untrained observers sometimes confuse them, especially bitterness and sourness (Hettinger, Gent, Marks, & Frank, 1999; Meiselman & Dzendolet, 1967; O'Mahony, Goldenberg, Stedmon, & Alford, 1979; Robinson, 1970). Some have argued that a taste continuum, where bitter, salty, sour, and sweet would only be familiar points, would more accurately describe gustatory perception, as mixtures of basic tastes are

often perceived as unitary (Schiffman & Erickson, 1980). Based on the results of multidimensional scaling (MDS), Schiffman and Erickson (1971) suggested a three-dimensional model of taste with hedonic value, molecular weight, and deviation from a pH of 7 as dimensions. However, the issue of basic tastes is still widely debated (see Erickson, 2008, for a recent review).

1.2.2 Categories of odours

When it comes to odours, it is even harder to come up with a classification system than for tastes. Based on the study of specific anosmias, Amoore (1977) attempted to define primary odours. He described six of them: sweaty, spermous, fishy, malty, urinous, and musky. He hypothesised the existence of a minimum of 32 primary odours. Given that his conception of a primary odour was one that is detected by a specific receptor, he largely underestimated their number, as the number of receptor types is now estimated to be about 1000, 350 of which are expressed (Buck & Axel, 1991; Glusman, Yanai, Rubin, & Lancet, 2001). A more complex system is found in the American Society for Testing and Materials' *Atlas of Odor Character Profiles* which includes 146 terms, separated into 11 categories (Dravnieks, 1985). Interestingly, this system includes *sweet*, *sour*, and *bitter*, which are taste descriptors, thus acknowledging the complex interactions between the two modalities (see Section 1.2.3). But none of these systems seems to be widely agreed upon. Specific systems were developed for certain product categories, such as wine (Noble et al., 1984), but they are only used by experts and require training. Another approach has been to use multidimensional scaling (MDS, based on similarity ratings) or semantic differential scaling to find the main dimensions representing odours (e.g., Dalton, Maute, Oshida, Hikichi, & Izumi, 2008; Schiffman, Robinson, Louis, & Erickson, 1977). MDS has been shown to produce consistent results no matter whether experts or average consumers are tested (Lawless, Clatter, & Glatter, 1990). The dimension of hedonic value (or pleasantness) is consistently found. Dalton et al. (2008) suggested the use of the dimensions

described by Osgood (1952) for other types of stimuli: evaluation, activity, and potency. Meanwhile, Zarzo (2008) suggested edibility as a second dimension in addition to hedonic value. Pleasantness is even suggested to be the only dimension of odours by some (Yeshurun & Sobel, 2010). Odour objects would then correspond to the external pleasantness of the odorant, combined with internal pleasantness, which is affected by mood, temperature, and hunger. This view is consistent with the idea that the function of olfaction is to elicit an approach or avoidance behaviour: approach of food when hungry, of safe environment, or of a potential mate; and avoidance of toxic substances, or predators. The major problem with many classification systems is that they rely on subjective descriptions of odours, and are thus subject to the effects of context, experience, and/or cultural background. Even for measures of similarity, different criteria might be used. It has thus been suggested that a better approach would be to use measures of performance, such as discrimination (Wise, Olsson, & Cain, 2000).

1.2.3 The multisensory perception of flavour

Gustation is certainly not sufficient in-and-of-itself to fully experience food. The decrease in "taste" experienced when the nose is blocked underlines the essential role that olfaction plays in the perception of flavour. Taste perception is influenced by many other factors: colours, touch, temperature, irritants, texture, or sounds (see Auvray & Spence, 2008; Delwiche, 2004; Prescott, 1999; Shepherd, 2006; Small & Prescott, 2005; Stevenson, 2009; Stillman, 2002; Verhagen & Engelen, 2006; see also section 1.2.4). However, there is something unique about taste-odour interactions, as in most cases they are unconscious, and the combination of taste and retronasal[2] smell is experienced as a single percept localised to the mouth (a phenomenon known as oral referral; Rozin, 1982). Three main factors have been shown to affect the extent to which taste and smell interact. First, the taste-odour pair must be congruent: For example, strawberry odour was demonstrated to enhance sweetness ratings of a sucrose solution, while

[2] Retronasal refers to smells originating from the mouth, perceived when exhaling, in contrast to orthonasal, which refers to smells outside the mouth, perceived when inhaling.

peanut butter had no effect (Frank & Byram, 1988; see also, Prescott, 1999, for a review). Second, the taste and the odour must occur at the same time, and the odour must be smelled retronasally (see Lim & Johnson, 2011, for a recent review). Third, attention can modulate the integration and, depending on the cognitive strategy used, taste and smell components of the flavour can, in some cases, be assessed separately (Small & Prescott, 2005). Tactile stimulation in the mouth also seems to facilitate the binding of taste and smell sensations to a food item (Green, 2003; although see Lim & Johnson, 2011). In the same way that we perceive a visual scene as a whole, even though form, motion, and colour are analysed by separate neural systems, we thus seem to get a percept of flavour that integrates taste, smell, and trigeminal stimulation (Abdi, 2002).

In the present thesis, *taste* will be used to describe pure gustatory sensations, while *flavour* will be used to describe the combination of taste, smell, and, where relevant, trigeminal stimulation.

1.2.4 Crossmodal associations and interactions with taste and smell

Given the interplay of all sensory modalities in the evaluation of food, it should come as no surprise that associations of sensory features that often occur together (such as the colour, shape, and flavour of a fruit) are learned and can then influence perception and behaviour. Recently, it has been shown that odours can direct attention in a visual scene (Seigneuric, Durand, Jiang, Baudouin, & Schaal, 2010). For example, an odour of orange can direct attention to an orange presented visually among other objects. The presentation of the odour or flavour of a fruit can also facilitate the subsequent movement to grasp it (Castiello et al., 2006; Parma et al., 2010). Colours interact with odours and flavours in a variety of ways (see Spence, Levitan, Shankar, & Zampini, 2010, for a recent review). Some colours are preferentially associated with specific odours, both in explicit and implicit tasks (e.g., pink with strawberry; Demattè, Sanabria, & Spence, 2006). When a white wine is coloured red with an odourless dye, tasters will describe

its odour mostly with terms usually attributed to red wine (Morrot, Brochet, & Dubourdieu, 2001; see also Parr, Geoffrey White, & Heatherbell, 2003). Note, however, that both novices and experts are able to identify red, white, and rosé wine at above chance level in the absence of visual cues (Ballester, Abdi, Langlois, Peyron, & Valentin, 2009). Brown sugar-coated chocolates are rated as more chocolaty than green ones (Shankar, Levitan, Prescott, & Spence, 2009). Inappropriate colours have been shown to increase the error rate in an odour discrimination task. However, this effect disappears with an articulatory suppression task, suggesting that the effect is mediated by conceptual, rather than perceptual, means (Stevenson & Oaten, 2008). It has been demonstrated that a higher perceived congruency between colours and odours presented simultaneously results in increased activity in regions of the orbitofrontal cortex and the insular cortex (Österbauer et al., 2005). The associations between odours (or flavours) and colours seem to go beyond learning which colour natural odorants usually are. Some perceptual dimensions of odours seem to vary systematically with dimensions of colours: When participants are asked to match colours with odours, colour lightness is inversely correlated with odour intensity (Gilbert et al., 1996; Kemp & Gilbert, 1997).

More surprisingly, taste and smell also induce associations with sensory features that do not co-occur in food products. These associations are sometimes used metaphorically when describing food. As early as the first century BC, Lucretius theorized that pleasant smells were composed of smooth particles, while unpleasant ones were composed of hooked particles (cited in Classen, Howes, & Synnott, 1994, p. 48). The use of shapes or textures to describe flavour is commonly used in descriptions of wine (e.g., round, rugged, silky, thin; Lehrer, 2009). Associations of flavours with shapes seem to be present even for products that are usually not described in terms of shapes, such as beer (Deroy & Valentin, 2011), or chocolate (Ngo, Misra, & Spence, 2011). Certain pairs of odours and abstract symbols are felt to be more congruent than others, and the simultaneous presentation of such congruent abstract symbols and odours has

been shown to modulate the reported intensity and pleasantness of the odour (Seo et al., 2010).

1.2.5 Conceptualisations based on taste and smell

The experience of food can induce conceptualisations about a product. In their study of dark chocolate, Thomson, Crocker, and Marketo (2010) split these conceptualisations in three categories: functional, emotional, and abstract. Interestingly, they show that these conceptualisations can be linked to sensory properties of the product: More bitter chocolates are described as confident, adventurous, and masculine, whereas more sweet and creamy chocolates are seen as fun, easy-going, and comforting. Conversely, taste adjectives can be used to describe behaviours and people metaphorically (e.g., sweet, bitter). Accordingly, people who like sweet foods are judged to be more agreeable, and preference for sweet foods actually predicts prosocial personalities, prosocial intentions, and prosocial behaviours. Even savouring a sweet food can momentarily increase helping behaviour (Meier, Moeller, Riemer-Peltz, & Robinson, 2012). There is also some indication that taster status might be correlated with certain aspects of personality (Utermohlen, 2002).

Another concept linking food with a more abstract meaning is disgust. Moral and physical disgust are very similar: They elicit similar facial motor activity (Chapman, Kim, Susskind, & Anderson, 2009), and rely on similar brain regions (Schaich Borg, Lieberman, & Kiehl, 2008). Sensory stimuli can even affect moral judgements. Tasting a bitter beverage has been shown to induce harsher moral judgements (Eskine, Kacinik, & Prinz, 2011), while being in a clean-scented room promotes reciprocity and charitable behaviours (Liljenquist, Zhong, & Galinsky, 2010). These conceptualisations based on food seem to vary with cultural background, as food-related words are not used in the same way in different languages to create metaphors (Depierre, 2009).

1.2.6 The role of expectations and context in chemosensory perception

Context can greatly affect chemosensory perception. Sensory properties, pleasantness, and acceptability can be affected by a variety of factors: colours (Davis, 1981; Herz, 2003; Herz & von Clef, 2001; Morrot et al., 2001; Seo, Buschhüter, & Hummel, 2008; Shankar et al., 2009), ambient lighting (Oberfeld, Hecht, Allendorf, & Wickelmaier, 2009), labels (Djordjevic et al., 2008; Hoegg & Alba, 2007; Shankar et al., 2009; Yeomans, Chambers, Blumenthal, & Blake, 2008), location (Bell, Meiselman, Pierson, & Reeve, 1994; Edwards, 2003), or selective attention to particular features of the stimuli (Marks, 2003).

These various effects presumably work through the modification of expectations prior to tasting or smelling the stimuli. Following a Bayesian approach, the expectations would modify the prior, and thus influence the final percept. This influence would be greater when the original signal is noisy (Knill & Pouget, 2004). However, this approach is unable to explain results where the expectations are very different from the actual product. In such cases, the expectations are recognised as violated and the effect is reversed. Such effects are better explained by the assimilation-contrast theory (Deliza & MacFie, 1996; Scharf, 2000). This theory hypothesise the existence of a threshold of the difference between expectations and perception separating two opposite behaviours: Under the threshold, the perception is biased toward the expectation (assimilation); Above the threshold, the difference is too big to be ignored, and is even exaggerated.

1.2.7 The role of hedonic value and emotions in chemosensory perception

Olfaction and gustation are probably the two senses in which liking is often more important than identification. Most people are perfectly happy not to know the detailed composition of their favourite perfume. In the same way, when in a restaurant, most people don’t need, or want, to analyse the various ingredients in their dish as long as the food tastes

good. Thus, the function of gustation and olfaction seems to be mostly to induce approach or avoidance behaviours.

Following these observations, it has even been suggested that pleasantness is the only perceptual dimension of odours (Yeshurun & Sobel, 2010; see Section 1.2.2). However, odours seem able to elicit more complex emotions than approach-avoidance based on hedonic value. Reactions to odours can be measured through heart rate and skin conductance. Heart rate has been shown to correlate with pleasantness measures, while skin conductance correlates with arousal. Arousal ratings also correlate with intensity ratings (Bensafi et al., 2002). Approaches based on basic emotions or dimensional models might not be appropriate to measure emotions elicited by odours. A new model, the Geneva emotion odour scale (GEOS), has recently been developed (Chrea et al., 2009) and shown to outperform the two classical models (basic emotions and dimensional) in terms of measuring affective responses to odours (Delplanque et al., in press). The model includes six classes of emotions: relaxation, unpleasant feeling, sensuality, refreshment, sensory pleasure, and pleasant feeling. Emotions elicited by odours seem to vary with cultural background. Scales developed using the same method in Britain and Singapore comprised of common dimensions (unpleasant feeling, pleasant feeling, refreshment, and sensuality) and dimensions that were culture specific (Ferdenzi et al., 2011).

Tastes have also been linked to emotions: Responses to basic tastes, measured through physiological parameters (heart rate, skin resistance, skin temperature, skin blood flow, and skin potential) demonstrated specific responses to the basic tastes. These responses also varied slightly according to gender. Men and women had similar responses to sweet, sour and bitter, but their response to salty were somewhat different: Men reacted with physiological reactions of surprise or disgust, while for women, disgust dominated, but happiness was sometimes also elicited (Robin, Rousmans, Dittmar, & Vernet-Maury, 2003). As for odours, the use of the basic emotions model to study emotional response to tastes and flavours has been suggested to be

insufficient. Specific questionnaires were thus developed, for example, for food products (39 terms; King & Meiselman, 2010), or for wine (16 terms; Ferrarini et al., 2010). Desmet and Schifferstein (2008) used a list of 22 emotions, and suggested five categories of sources of food emotions: Sensory attributes, experienced consequences, anticipated consequences, personal or cultural meaning, and actions of associated agents (e.g., the cook).

Conversely, induced emotional states can affect chemosensory perception. Olfactory sensitivity has been shown to be reduced after the presentation of unpleasant pictures, and, for men only, also after the presentation of pleasant pictures, compared to neutral pictures. Both types of pictures also affected pleasantness ratings of odours (Pollatos et al., 2007).

In the case of taste, joy and sadness elicited by movie clips influenced the pleasantness and sweetness ratings of a sweet drink, but not of a bitter or a bitter-sweet drink. The facial reactions to the drinks remained unchanged (Greimel, Macht, Krumhuber, & Ellgring, 2006). Similarly, induced joy or sadness in men can affect the pleasantness of chocolate. Joy also increased appetite and quantity of chocolate eaten, while sadness decreased both variables (Macht, Roth, & Ellgring, 2002).

In conclusion, chemosensory perception can both elicit emotions, and be influenced by them.

1.2.8 The role of familiarity and expertise in chemosensory perception

Experience shapes the perception of chemosensory stimuli from the very first stages of development. Immediately after birth, neonates show preference for flavours present in their mother's diet during pregnancy (Schaal, Marlier, & Soussignan, 2000). In the first few days after birth, rabbits can pair a novel odour to a pheromone that induces suckling and then respond to it by displaying suckling behaviour. After weaning, they also show a higher sensitivity and preference for foods that were included in their mother's diet (Hudson, 1999). Familiarity can also profoundly affect how stimuli are perceived and evaluated by adults: Everyday odours that

are rated as more familiar are also rated as more intense and more pleasant, regardless of cultural background (Distel et al., 1999; although see Delplanque et al., 2008). Familiarity with odour-taste pairs modulates interactions between the two modalities and influences the perception of the combination as a unique flavour percept (Small & Prescott, 2005).

Extensive training with specific products can greatly impact performance. In the case of wine, which is one of the most studied products in terms of expertise, the level of expertise impacts performance in various ways depending on the tasks used. Wine experts seem to have similar olfactory thresholds as novices (Parr, Heatherbell, & White, 2002) and to use the same perceptual dimensions to discriminate stimuli (Chollet & Valentin, 2000). However, experts are better at wine-related odour recognition (Parr et al., 2002). When it comes to verbal tasks, experts perform better in some tasks, such as using language to describe stimuli (Chollet & Valentin, 2000; Lawless, 1984), but not in wine-related odours identification (Parr et al., 2002).

1.3 Audition and music

1.3.1 The role of emotion in music

The role of emotion in music is two-fold: First, composers and performers express emotion through music; Second, emotions can be induced in listeners (Collier, 2007; Scherer, 2004; Zentner, Grandjean, & Scherer, 2008). Listening to music activates the dopaminergic system similarly to more concrete types of rewards, such as food or money (Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011). Musically-induced emotions can prime responses to visual emotions (e.g., faces; Logeswaran & Bhattacharya, 2009). Some musical parameters (e.g., pitch, tempo, timbre) have been linked to specific emotions (Hailstone et al., 2009; Hevner, 1937; Juslin, 2000). For example, positive emotions in response to the major mode, and negative emotions in response to minor mode seem to be present even in young children, at least in Western cultures (Pinchot Kastner & Crowder, 1990). Some of these low-level parameters even seem to be consistent across cultures (Balkwill & Thompson, 1999; Fritz et al.,

2009). The performer also plays a role in what is evoked (Bhatara, Tirovolas, Duan, Levy, & Levitin, 2011). Expressive intention can even be communicated through low-level acoustic parameters in improvisations on a single piano note by both musicians and non-musicians (Baraldi, Poli, & Rodà, 2006).

1.3.2 Evocation of concepts through sound and music

As well as emotions, music can convey a variety of more specific meanings, which are influenced not only by the composition itself, but also by the performer and the listener. In some cases, however, the intention of the composer was clearly to represent characters (e.g., Prokofiev's *Peter and the Wolf*), animals (Saint-Saëns's *Carnival of the Animals*), natural elements (Debussy's *The Sea,* Holst's *The Planets*), or even paintings (Mussorgsky's *Pictures at an Exhibition*) through their music.

There is some evidence that music can express aspects of people, such as their age, gender, and/or emotional state (Watt & Ash, 1998; Watt & Quinn, 2007). Moreover, musical excerpts can be described in terms of bodily motion (Eitan & Granot, 2006). The perception of "groove" (wanting to tap one's feet or dance) is related to specific rhythmic properties, some of which, such as rhythmic density between beats and the salience of beats, are general across musical genres (Madison, Gouyon, Ullén, & Hörnström, 2011). Musical excerpts can also prime the meaning of words in the same way as semantically related sentences (Koelsch et al., 2004), while music in movies can influence the likeability of characters, as well as the feelings that are attributed to them by viewers (Hoeckner, Wyatt, Decety, & Nusbaum, 2011).

Auditory parameters can be represented metaphorically, e.g., vertical location for pitch, or amplitude for size. Trained musicians are more consistent than musically naïve participants when choosing such metaphors, whereas cultural background has a more limited effect (Walker, 1987). In a more practical approach, it has also been demonstrated that when representing certain types of data by specific acoustic parameters of auditory displays (e.g.,

temperature by loudness) some pairings lead to better performance than others, and that the direction of the pairing (e.g., high temperature paired with louder or softer sounds) is important (Walker & Kramer, 2005).

1.3.3 Crossmodal associations with pitch

There are a number of crossmodal associations with the pitch of musical notes, and some of these associations are commonly used when talking about music metaphorically. These metaphors vary across cultures (Ashley, 2004; Shayan, Ozturk, & Sicoli, 2011). However, it has been demonstrated that people can usually guess the direction in which a metaphor is used in a culture they are not familiar with (Eitan & Timmers, 2010). Moreover, some of these associations (with size and brightness) are also found in young children, suggesting that they are not mediated by language, but reflect a more fundamental aspect of perception (Mondloch & Maurer, 2004).

The most obvious association with pitch in Western culture is verticality (Pratt, 1930). These two dimensions have been shown to interact and both Garner and Stroop interference have been observed in a speeded classification task (Hubbard, 1996; Melara, 1989; Melara & O'Brien, 1987; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Other dimensions that Western participants readily associate with pitch include brightness, even if this dimension is less commonly used in metaphors. In a series of experiments, Marks (1982) demonstrated that people consistently chose higher pitch for the "sound of sunlight" than for the "sound of moonlight", for example, while a cough was considered to be "darker" than a sneeze (see also Marks, 1974).

1.4 Interactions between chemosensory and auditory stimuli

After examining the chemical senses and audition separately, the various ways in which they interact will now be surveyed. Section 1.4.1 deals with the contribution of the sounds

made by food when consumed (e.g., chewing and biting sounds) to the perception and evaluation of food stimuli. Section 1.4.2 explores the influence of background music or noise on behaviours related to food. Cases of synaesthesia involving taste or smell are examined in Section 1.4.3. Finally, crossmodal associations between sounds and taste (Section 1.4.4) or odours (Section 1.4.5) are described.

1.4.1 Sounds made by the consumption of food

Auditory cues can convey information about the physical properties of food items through the sounds produced when biting into or chewing them (Vickers & Wasserman, 1980). Sounds have been shown to constitute an essential part of people's judgements of crispness, crunchiness, and hardness. What is more, listening to recordings of biting and chewing sounds has been shown to lead to similar ratings of those attributes than when actually tasting the same food items (Vickers, 1981). Potato chips are perceived as crispier and fresher when the auditory feedback is modified to increase the overall intensity or the high frequency sounds (Zampini & Spence, 2004). Pitch appears to be a factor in differentiating between crispness and crunchiness (Vickers, 1984). However, vibrations conducted through the bones might be largely responsible for the perception of crispness as blocking auditory cues does not always affect crispness ratings (Christensen & Vickers, 1981). Moreover, a recent study demonstrated that the effect of blocking auditory cues was modulated by other sensory modalities when evaluating the crispness of biscuits: When the auditory cues were masked by the loud sounds of breaking crispy foods played over headphones, the ratings for attributes such as crumbly were only affected when the participants closed their eyes as well (de Liz Pocztaruk et al., 2011). Sounds can also play a role in the detection of carbonation in drinks (Zampini & Spence, 2005). Sounds made by food thus seem to provide important cues about food items. However, when audition is blocked, the lack of auditory information can be compensated for to some extent by the information provided by other sensory modalities.

1.4.2 Influence of background music and noise

The auditory background can affect behaviours related to food and drinks in a variety of ways. First, music can influence people' behaviour in shops, when food is bought. The tempo of the music playing in the background influences the pace of in-store traffic flow as well as sales (Milliman, 1982). The type of music playing in a wine store can also affect how much money is spent: It has been reported that classical music leads consumers to buy somewhat more expensive wines than Top-Forty music (Areni & Kim, 1993). Moreover, playing typical French or German music can increase the sales of French or German wine, respectively (North, Hargreaves, & McKendrick, 1997, 1999). Preference for the music playing in the background has also been shown to affect the amount of time people spent in a supermarket (Herrington, 1996).

Second, the auditory background can affect behaviour in places where food and drinks are consumed, such as restaurants, cafeterias, and bars. Consistent with the results obtained for shops, playing classical music in a student cafeteria (compared to easy-listening music or no music) increased the amount of money that the consumers were prepared to spend (North & Hargreaves, 1998). Classical music (as compared to pop music and no music) has also been shown to increase the amount of money spent in a restaurant (North, Shilcock, & Hargreaves, 2003). Listening to music while eating has been shown to correlate with an increase in food intake (Stroebele & de Castro, 2006). It also induces an increase in the consumption of soft drinks (McCarron & Tierney, 1989). In bars, drinking songs (compared to Top-Forty or cartoon music) increase the amount of time spent in the bar as well as the amount of money spent by patrons (Jacob, 2006). The loudness of music can also affect patron's behaviour: Playing louder music in bars has been shown to lead to an increase in alcohol consumption and to a decrease in the time spent by patrons to finish their drink (Guéguen, Jacob, Le Guellec, Morineau, & Lourel, 2008). Similarly to results in shops, both the tempo of the music and musical preferences

of patrons influence the time they spend in a restaurant (Caldwell & Hibbert, 2002; Milliman, 1986; see also Spence & Shankar, 2010, for a review).

Finally, background noise can also have a more direct influence on people's perception of food. The level of noise has been shown to affect both sound-related features such as crunchiness, and unrelated ones, such as sweetness and saltiness (Woods et al., 2011). In Woods et al.'s experiments, crunchiness was rated as higher in loud background noise, while sweetness and saltiness were rated as lower. These researchers also found an interaction between noise and food liking: Participants who liked the background noise more also liked the food better when tested in the loud noise condition. Conversely, music seems to increase the perceived sweetness of alcoholic beverages (Stafford, Fernandes, & Agobiani, 2012). Sweetness has also been shown to be perceived as more pleasant in the presence of loud noise or music (Ferber & Cabanac, 1987). The perception of odours is also affected by the auditory background: Verbal and non-verbal noise lowers performance in an odour discrimination task, while music does not affect performance (Seo, Gudziol, Hähner, & Hummel, 2011). The auditory background can thus affect behaviours related to food in a variety of ways and contexts.

1.4.3 Cases of synaesthesia involving tastes, flavours, or odours

In synaesthesia, the presentation of one stimulus elicits a concurrent, secondary perceptual experience. The most common form is the experience of colours in response to letters (Day, 2005). Cases involving the chemical senses are relatively rare, as compared to other forms (159 out of the 572 cases reported by Day, 2005; 2 out of 22 cases examined by Simner et al., 2006). There are a few historical case studies, as well as a few more recently reported cases: words eliciting tastes (Gendle, 2007; Jones et al., 2011; Pierce, 1907; Richer, Beaufils, & Poirier, 2011; Ward & Simner, 2003), tones and music eliciting coloured shapes and tastes (Luria, 1968), tastes eliciting shapes (Cytowic & Wood, 1982), musical tone intervals eliciting tastes (Beeli, Esslen, & Jäncke, 2005; Hänggi, Beeli, Oechslin, & Jäncke, 2008). Very few, if any, of these cases

involve pure tastes: Usually, it is a flavour percept that is elicited. In the case reported by Pierce (1907), the subject was anosmic, but various textural and trigeminal sensations were elicited in addition to taste (e.g., “cool, round rolling pieces, possibly nut”, “sweet, spicy, as if fumes were passing up through the nostrils”). The synaesthete E.S., described by Beeli et al. (2005), reported basic tastes in response to certain musical intervals, but also more complex sensations in response to others, for example “low-fat cream” in response to a major sixth. In the case reported by Gendle (2007), words also elicit complex sensations, such as “chicken nugget with sweet and sour sauce”. On top of these reported cases, it has been suggested that the attribution of taste qualities to odours (see Section 1.2.3) is very similar to synaesthesia: The associations are reliable, asymmetric, and automatic (Stevenson & Tomiczek, 2007). However, unlike in synaesthesia, there is no awareness that different sensory modalities are involved.

There are two main categories of theories to explain the mechanisms of synaesthesia: Cross-activation, which hypothesizes direct connections between the brain areas of the two concurrent sensory perceptions (Hubbard, Brang, & Ramachandran, 2011; Ramachandran & Hubbard, 2001), and disinhibition of feedback, according to which synaesthesia results from feedback connections from multisensory areas (Grossenbacher & Lovelace, 2001). However, these mechanisms are mostly based on studies of grapheme-colour synaesthesia. Many forms of synaesthesia have been reported, and the term might actually encompass distinct groups of individuals (Novich, Cheng, & Eagleman, 2011). In their study of lexical-gustatory synaesthesia, Ward and Simner (2003) suggested that this particular form of synaesthesia is mediated by a conceptual level of representation, rather than being the result of innate direct connections between two perceptual systems, thus supporting the disinhibition of feedback hypothesis (see also Simner & Haywood, 2009). The disinhibition of feedback theory would also allow for a continuum between synaesthetes and non-synaesthetes. Following this approach, crossmodal associations could be viewed as a weak form of synaesthesia, as suggested by Martino and Marks (2001; although see Spence, 2011).

1.4.4 Crossmodal associations between taste and sounds

In Huysmans's novel *Against Nature* (1884), the main character, Des Esseintes, uses a "mouth organ" to mix liqueurs. According to him, the taste of each liqueur corresponds to a musical instrument: Kirsch corresponds to the trumpet, and whisky to the trombone, for example. He thus uses the organ to "transfer specific pieces of music to his palate" or to compose new ones. Should Des Esseintes be considered a synaesthete? Or are his correspondences based on crossmodal associations present in non-synaesthetes as well? There are a few reports of crossmodal associations between sounds and tastes (or more accurately, flavours) in the scientific literature. One early study reported that, when asked to choose a pitch to match to the flavour of a beer, participants reliably chose a specific pitch according to the type of beer (Holt-Hansen, 1968). However, a follow-up study by Holt-Hansen (1976) suggests that his participants might actually have been synaesthetes, given the very rich experiences they describe. Moreover, Holt-Hansen's results were only partially replicated in a later study with other food and drink items: Although a weak effect was found, the participants found the task very difficult and none reported similar experiences to Holt-Hansen's participants (Rudmin & Cappelli, 1983).

Apart from musical sounds, sounds from language can also elicit crossmodal associations. Traditionally, language has primarily been seen as an arbitrary matching of words to meaning (de Saussure, 1916), with just a few notable exceptions (e.g., as in the case of onomatopoeia). However, the idea that letters can be linked to sensory features (mostly motion, shape, or size) dates as far back as the fourth century BC. In one of his dialogues, *Cratylus*, Plato writes that the sounds of a word express the essence of the concept it represents ([H. N. Fowler Trans.], 1921). In the first century BC, Dionysus of Halicarnassus extend these links to tastes, mentioning that λ is the sweetest of the semi-vowels ([W. Rhys Robert Ed. & Trans.], 1910). Early reports by Köhler (1929, 1947) demonstrated that, when asked to pick the meaningless non-word ("maluma" or "takete") that matches abstract shapes, participants reliably chose the soft-sounding "maluma"

for a rounded, cloud-like shape, and the sharply-inflected sounds of “takete” to represent a spiky, star-like shape. Since then, sound symbolism has been further explored in a variety of languages (Fónagy, 2001; Hinton, Nichols, & Ohala, 1994). The impact of sound symbolism in the case of food evaluation was highlighted by Yorkston and Menon (2004). They demonstrated that participants expected a creamier, richer, and smoother ice cream when it was named “Frosh” rather than “Frish”. Early results by Fónagy (1963) had also demonstrated that children and adults both report *u* to be more bitter than *i*, and *m* and *l* to be sweeter than *k* and *t*. Gallace, Boschin, and Spence (2010) demonstrated that food items could be reliably described by non-words. In their study, participants were presented with various food items (e.g., chocolate, crisps, or cheese) and asked to rate them using anchored visual analogue scales, where the endpoints could be non-words such as “kiki” and “bouba”, or “maluma” and “takete”. Ngo, Misra, and Spence (2011) extended these results, by demonstrating that even variations in similar food products, such as the cocoa content in chocolate, led to consistent crossmodal associations between the taste/flavour of the chocolate and non-words or shapes.

Following the early results reported in this thesis (Experiment 2.1), crossmodal associations between phonetic features of sounds and basic tastes have been reported (Simner, Cuskley, & Kirby, 2010). It has also been demonstrated that musicians asked to improvise based on taste adjectives (bitter, salty, sour, or sweet) use similar musical parameters in order to represent the different tastes. These parameters are consistent enough for decoding methods to make binary choices between two taste words above chance level. Moreover, non-musicians can also reliably guess the basic taste when listening to such improvisations (Mesz, Trevisan, & Sigman, 2011).

1.4.5 Crossmodal associations between odours and sounds

Reports of crossmodal associations between odours and sounds are very limited, although a number of associations between odours and other sensory modalities have been

reported (see Section 1.2.4). The existence of crossmodal associations between odours and pitch have been demonstrated in one study using materials commonly used in commercial perfumery (Belkin, Martin, Kemp, & Gilbert, 1997). Moreover, Belkin et al. suggest that the study of crossmodal associations between odours and other sensory modalities or dimensions (e.g., auditory timbre) could help better characterize the key perceptual dimensions of odour quality.

1.5 Outline of the experimental research

The research presented in this thesis revolves around three main goals:

- Demonstrating the existence of, and characterising, crossmodal associations between chemosensory and auditory stimuli
- Suggesting potential mechanisms for these crossmodal associations
- Evaluating the influence that these crossmodal associations might have on perception when chemosensory and auditory stimuli are presented simultaneously.

The experiments reported in Chapter 2 used implicit tasks: The implicit association test (IAT) and the go/no-go association task (GNAT). These types of task require participants to use the same response key for two categories (a basic taste and high- or low-pitched sounds). Better performance for a certain pairing of categories is assumed to reflect an implicit association between these categories. In these experiments, the basic tastes were evoked by names of food and drink items.

In Chapter 3, these results were confirmed using a variety of chemosensory stimuli: solutions of basic tastes and flavours (Experiment 3.1), flavoured milk solutions (Experiment 3.2), crisps (Experiment 3.3), and wine-related odours (Experiment 3.4). In this series of experiments, an explicit task was used: The participants selected a musical note to associate with a chemosensory stimulus. Musical notes played by four types of musical instruments at 13

pitches were used. Ratings for a variety of features of the chemosensory stimuli were obtained in order to uncover possible factors underlying the crossmodal associations.

Two such factors were selected to be studied in more details in Chapter 4: familiarity (Experiment 4.1) and pleasantness (Experiment 4.2). The role of the familiarity of the chemosensory stimuli was studied in Experiment 4.1 by comparing the associations with wine-related odours made by a group of regular wine tasters with those made by a control group. Experiment 4.2 focused on the pleasantness dimension, by studying crossmodal associations between musical notes and different types of chocolate.

First steps towards the third goal were taken in Chapter 5. Experiment 5.1 examined the effect of background soundtracks on the perception of a food item (cinder toffee). Experiment 5.2 focused on odours and musical notes presented simultaneously.

Finally, Chapter 6 presents a summary of the key findings, followed by a discussion of the theoretical implications as well as practical applications that might results from the research presented in this thesis. Directions for future research are also suggested.

2 Chapter 2: Implicit associations between basic tastes and pitch

2.1 Introduction

A sensible first step if one wants to explore the nature of any crossmodal associations between tastes and sounds is to try and demonstrate their existence in neurocognitively normal individuals. Evidence on this topic from previous research is scarce (see Section 1.4.4). One of the few studies to have dealt directly with the crossmodal links between sound and taste perception was reported by Holt-Hansen (1968), who reported that the pitch associated with the taste of two different brands of beers was different (though no statistics were included). In a subsequent study, Holt-Hansen focused on the extraordinary experiences described by a subset of his participants (Holt-Hansen, 1976). Unfortunately, however, these studies were not followed up by generalising the effect to other food or drink items. What is more, they were only partially replicated in a subsequent study conducted by another group of researchers (Rudmin & Cappelli, 1983). Nonetheless, Holt-Hansen's studies do at least suggest that pitch may be an aspect of auditory stimuli that can be associated with specific tastes.

One issue with Holt-Hansen's experiments is that in his 1976 study, he focused on those participants who apparently reported 'extraordinary experiences' when the beer was tasted at the 'pitch of harmony'. These experiences seem similar to those induced by hallucinogens or possibly to those reported by at least certain synaesthetes (Nichols, 2004). Holt-Hansen's results might thus be based on some of his participants being synaesthetes, although cases of synaesthesia involving tastes (or flavours) and sounds are rare, even amongst synaesthetes, who themselves are a rare breed (Beeli et al., 2005; Day, 2005; Luria, 1968; see also Section 1.4.3).

To explore possible associations between basic tastes and pitch, an Implicit Association Test (IAT; Greenwald, McGhee, & Schwartz, 1998) was first used in Experiment 2.1. The IAT is well-suited to testing associations that might not be accessible consciously. It has already been

used successfully (in a somewhat modified version) in order to investigate crossmodal associations (Demattè, Sanabria, & Spence, 2007). The IAT is based on the principle that if two categories or concepts are associated, then it should be easier to respond to both using a single response key than if they are not. By now, the IAT is a well-established and reliable methodology/paradigm, and several follow-up studies have been designed to improve both its design and the related scoring algorithm for assessing participants' performance (Greenwald & Nosek, 2003; Nosek, Greenwald, & Banaji, 2005; Nosek, Greenwald, & Banaji, 2006). However, one weakness with the task that was identified early on is that it is designed to test the strength of a pair of associations, rather than the strength of a single association. Therefore, in Experiment 2.2, a new task, similar in concept, but allowing for the measure of individual associations, was used: the go/no-go association task (GNAT; Nosek & Banaji, 2001). In both experiments, the names of drinks and food items were used as exemplars of basic taste categories (bitter, salty, sour, and sweet; umami was left out due to its unfamiliarity to the majority of British participants). Although a preliminary survey was used to select the bitter and sour items (as these two tastes are the most easily confused), most common food items contain a mixture of basic tastes. A control experiment (Experiment 3) was thus run to check that the items chosen were classified into four distinct categories, using multidimensional scaling (MDS).

2.2 Experiment 2.1

2.2.1 Methods

2.2.1.1 Participants

The experiment was approved by the Central University Research Ethics Committee of Oxford University. The participants gave their informed consent prior to taking part in the study, reported normal or corrected-to-normal vision, and no hearing impairment. The participants were recruited through a mailing list and were primarily students from the Department of Experimental Psychology, Oxford University. Each of the two parts lasted for approximately 20

minutes and the participants were compensated for their time by a £5 (UK Sterling) gift voucher or by course credits (for psychology undergraduates). Twenty-eight participants took part in the first part of Experiment 2.1 (14 males, aged 20-38 years). Twenty-eight participants (some of which had taken part in the first part of Experiment 2.1) took part in the second part (18 males, aged 19-40 years).

2.2.1.2 Stimuli

Given that the taste adjectives 'sour' and 'bitter' are commonly confused in English (Hettinger et al., 1999; Meiselman & Dzendolet, 1967; O'Mahony et al., 1979; Robinson, 1970). A preliminary online survey was conducted initially in order to select eight food or drink items (from a list of 36 possible items) classified as either sour or bitter by the majority of respondents (minimum of 65% of respondents). The items that were finally chosen consisted of: coffee, beer, tonic water, and dark chocolate for the bitter-tasting foodstuffs and lime, lemon, vinegar, and pickles for the sour-tasting foodstuffs. Lemon was then replaced by lemon juice in order to better match the length of words and food/drink ratio in the two categories. The food items for salty and sweet were chosen without conducting a preliminary survey as, in contrast to bitter and sour, there is no confusion between these two basic tastes. The salty stimuli consisted of broth, crisps, pretzel, and salt. The sweet stimuli consisted of honey, maple syrup, sugar, and vanilla (see Table 2.1 for the complete list of stimuli). These visual stimuli were presented on a 75 Hz refresh rate CRT monitor (CTX 5320).

Table 2.1: Visual stimuli used in Experiment 2.1 and 2.2.

Category	Bitter	Salty	Sour	Sweet	Neutral
Stimuli	Beer Coffee Dark chocolate Tonic water	Broth Crisps Pretzel Salt	Lemon juice Lime Pickles Vinegar	Honey Maple syrup Sugar Vanilla	Bread Fork Spoon Water

The auditory stimuli were taken from an online musical instrument samples database from the University of Iowa Electronic Music Studios (http://theremin.music.uiowa.edu/MIS.html, downloaded on 04/03/09). The high-pitched sounds consisted of a C6 (1046.5 Hz) played on a clarinet, a piano, a violin, and a trumpet. The low-pitched sounds consisted of a D2 (73.4 Hz) played on a bassoon, a piano, a cello, and a bass trombone. The sounds were edited to last for 2000 ms, and were presented over closed headphones (Beyerdynamic DT 531) at a loudness of 70 dB (± 1 dB).

2.2.1.3 Procedure

The IAT was programmed in E-Prime, following the design described by Greenwald et al. (1998), incorporating the later suggestions for improvement made by Greenwald et al. (2003). In Part 1, the first block of 24 trials consisted of practice at the bitter-sour classification task (3 trials per name of food item). The second block consisted of practice at the pitch classification task and also included 24 trials. The third and fourth blocks consisted of the first combined task (16 and 48 trials, respectively). For half of the participants, the same key was pressed for high-pitched sounds and bitter-tasting food names. For the other half of the participants, the high-pitched sounds and sour-tasting food names were initially associated with the same response key. The fifth block of 24 trials again consisted of practice, this time of the bitter-sour classification with the response keys reversed. The sixth block consisted of the second combined task. As suggested by Nosek et al. (2005), the number of trials in this block was increased (to 32), as it has been shown to reduce the order effect (Greenwald & Nosek, 2003). The seventh and final block was composed of 48 trials of the reversed combined task (see Table 2.2 for a full listing of block types). The third and sixth blocks were originally designed as practice, hence their shorter length, but we followed Greenwald and Nosek's (2003) suggestion and included them in the data analysis.

Instructions were provided to the participants before each block of trials, describing the task and the response keys to be used (*a* and *l* on the computer keyboard). The names of the

categories remained on the right and left sides of the screen throughout the blocks as a reminder to the participants. In case of an erroneous response, the word *error* appeared on the screen for 307 ms in 18 pt red font.

Since they didn't change throughout the experiment, the response keys used to respond to the high- and low-pitched sounds were counterbalanced across participants. The order of the two pairings was also counterbalanced between participants, resulting in four different conditions between subjects. The procedure was identical in Part 2, with names of salty and sweet food items (see Table 2.2).

Table 2.2: Summary of the IAT blocks from Experiment 2.1. The order of the blocks was counterbalanced such that half of the participants started with the sour and high-pitched association in blocks 3 and 4. The response keys used were also counterbalanced, with half of the participants responding to low-pitched sounds with the left key. In Part 2, sour and bitter were replaced by sweet and salty.

Block	Task	Left key response	Right key response	No of trials
1	Single task	sour	bitter	24
2	Single task	high-pitched	low-pitched	24
3	Combined task	sour / high-pitched	bitter / low-pitched	16
4	Combined task	sour / high-pitched	bitter / low-pitched	48
5	Reversed single task	bitter	sour	24
6	Reversed combined task	bitter / high-pitched	sour / low-pitched	32
7	Reversed combined task	bitter / high-pitched	sour / low-pitched	48

After the IAT, the participants filled out a short questionnaire in which they were asked for their age, sex, country of origin, mother tongue, and whether or not they played a musical instrument. The participants in Part 2 also rated the pleasantness of the food items named on a 7-point linear scale anchored with the labels *very unpleasant*, *neutral*, and *very pleasant*.

2.2.1.4 Data analysis

Reaction times (RTs) and error rates were recorded and analysed in two different ways. First, the scoring algorithm suggested by Greenwald and Nosek (2003) was followed. This algorithm consists in replacing latencies for error trials by the mean latency for the block plus two standard deviations. *D* values are then computed as the mean of the differences in RT between blocks 3 and 6 and between blocks 4 and 7, each divided by their pooled standard deviation. Second, RTs of the correct trials and error rates were compared between the two pairing conditions.

2.2.2 Results

A one-sample *t*-test was conducted on the *D* value (described above). This analysis revealed a statistically significant difference from zero in Part 1 (M = .30, SD = .50, $t(27) = 3.22$, p = .003). This indicates that the association between sour tastes and high-pitched sounds and between bitter tastes and low-pitched sounds was stronger than the association between sour tastes and low-pitched sounds and between bitter tastes and high-pitched sounds. A similar result was obtained in Part 2 (M = .29, SD = .47, $t(27) = 3.25$, p = .003), indicating that the association between sweet tastes and high-pitched sounds and between salty tastes and low-pitched sounds was stronger than the association between sweet tastes and low-pitched sounds and between salty tastes and high-pitched sounds. Interestingly, the magnitude of these effects was comparable to those obtained in other published IAT studies that have used the same scoring algorithm (e.g., D = .2 for odours-sickness association, Bulsing, Smeets, & Van den Hout, 2009; D = .34 for white-American association, Devos & Banaji, 2005).



Figure 2.1: Reaction times in Experiment 2.1 for congruent pairings (use of one response key for sour and high pitch, respectively for sweet and high pitch, and the other one for bitter and low pitch, respectively salty and low pitch) and for incongruent pairings (use of one response key for sour and low pitch, respectively for sweet and low pitch, and the other response key for bitter and high pitch, respectively for salty and high pitch). Error bars represent the standard error of the means. ** indicates a significant difference ($p < .01$).

Paired-sample *t*-tests were also conducted to compare the RTs and error rates between the two pairings of the tastes and sounds. In Part 1, the participants did not respond significantly faster when sour tastes were paired with high-pitched sounds (and bitter tastes with low-pitched sounds; *M* = 846 ms, *SD* = 367) than when sour tastes were paired with low-pitched sounds (and bitter tastes with high-pitched sounds; *M* = 916 ms, *SD* = 352, $t(27) = 1.50$, $p = .144$, see Figure 2.1). In Part 2, the participants responded significantly more rapidly when sweet tastes were paired with high-pitched sounds (and salty tastes with low-pitched sounds; *M* = 581 ms, *SD* = 146) than when sweet sounds were paired with low-pitched sounds (and salty tastes with high-pitched sounds; *M* = 637 ms, *SD* = 149, $t(27) = 55.99$, $p = .009$, see Figure 2.1). In Part 1, participants made significantly fewer errors when sour tastes were paired with high-pitched sounds (*M* = 4.0%, *SD* = 4.94) as compared to when the sour tastes were paired with low-pitched sounds (*M* = 6.9%, *SD* = 5.92, $t(27) = 4.28$, $p < .0005$; see Figure 2.2). In Part 2, participants also made fewer mistakes in the congruent pairing condition, although the

difference between the two pairing conditions did not differ at the .05 significance level (*M* = 3.9%, *SD* = 4.2, *M* = 5.1%, *SD* = 4.5, *t*(27) = 1.92, *p* = .07, see Figure 2.2).



Figure 2.2: Error rates in Experiment 2.1for congruent pairings (use of one response key for sour and high pitch, respectively for sweet and high pitch, and the other response key for bitter and low pitch, respectively salty and low pitch) and for incongruent pairings (use of one response key for sour and low pitch, respectively for sweet and low pitch, and the other one for bitter and high pitch, respectively for salty and high pitch). Error bars represent the standard error of the means. ** indicates a significant difference ($p < .01$).

The gender of participants, country of origin (British vs. non-British), and practice with a musical instrument had no significant effect on the strength of the association, the RTs or the error rates. It should, however, be noted that all of the participants were UK residents, and that further experiments would be necessary in order to more fully explore cultural differences in these particular crossmodal associations.

The sweet-tasting food items were rated as being more pleasant than the salty-tasting items (*M* = 4.32, *SD* = .85, *M* = 3.65, *SD* = .75, *t*(27) = 3.28, *p* = .003), although both categories were rated as pleasant (i.e., above the 'neutral' point, equal to a score of 3 with a maximum of 6).

2.2.3 Discussion

Experiment 2.1 revealed that sour and sweet tastes tended to be associated with high pitch, while salty and sour tastes tended to be associated with low pitch, as shown by the *D*

measure. Taste-pitch associations do exist and are not restricted to one pair of basic tastes. In Part 1, the error data confirmed these results, while the RT data did not reach significance, whereas the reverse was true in Part 2. Moreover, RTs were much lower in Part 2. This might be due to a difference in task difficulty, as bitter and sour tastes are often confused, while salty and sweet are not (Hettinger et al., 1999).

One limitation of Experiment 2.1 is that the IAT does not allow one to compare the respective strengths of associations (Nosek, Greenwald, & Banaji, 2005). In order to do so, modified versions of the test must be used, such as the GNAT (Nosek & Banaji, 2001), which was used in Experiment 2.2. Another limitation is the use of names of food items, instead of gustatory stimuli. As the same limitation applies to Experiment 2.2, this issue is further discussed in the General Discussion (see Section 2.5).

Finding a similar concept or dimension associated with both pitch and basic tastes might explain why they are associated. A dimension often used in IAT studies is pleasantness. Sweet stimuli were rated as more pleasant overall than the salty ones. However, pleasantness ratings were not obtained from participants in Part 1. This topic is thus further discussed in Experiment 2.2, in which pleasantness ratings are available for all stimuli, and in the General Discussion (Section 2.5).

2.3 Experiment 2.2

2.3.1 Methods

2.3.1.1 Participants

28 participants took part in Experiment 2.2 (21 females, aged 19-40 years, 9 British).

2.3.1.2 Stimuli

The visual stimuli consisted of the same names of food items as those used in Experiment 2.1, as well as neutral words (see Table 2.1 for the complete list). The auditory stimuli were the same as in Experiment 2.1, edited to last for 1000 ms.

2.3.1.3 Procedure

Each word or sound was presented for 1000 ms or until the 'Space bar' was pressed. The participants were instructed to press the space bar if the word or sound belonged to target categories (e.g., sweet or low-pitched). Trials were separated by an inter-stimulus interval (ISI) of 150 ms. On-screen instructions were given before each block of trials, and the target categories were presented at the top of the screen, on the left and right sides, throughout the block, as a reminder to the participant.

The participants were first given some practice with the task, i.e., pressing the space bar when they saw a word, or heard a sound, belonging to one target category. To this end, they completed six blocks of 24 trials (one per category, presented in a random order). For each combined task (i.e., responding to one taste and one pitch in the same block), they then completed a block of 16 practice trials followed by a block of 64 test trials. Feedback was given after each practice trial (a green circle or a red cross presented on the screen for 100 ms). This ensured that participants were aware of the expected classification. The participants completed the eight combined tasks in a random order (i.e., four different tastes combined with high- or low-pitched sounds).

2.3.1.4 Data analysis

The approach described by Nosek and Banaji (2001) was followed, using signal detection theory (SDT, Green & Swets, 1966). *d'* was thus computed for each combined task (*z*(hit rate)-*z*(false alarm rate), where *z* is the inverse Gaussian function). Empty cells, which result in infinity when applying the *z* function, were replaced by 0.35 divided by the number of trials, as suggested by Banaji and Greenwald (1995).

2.3.2 Results

Paired-sample *t*-tests were conducted to compare the sensitivity (*d'*) of participants' responses to the target categories between blocks of trials in which the basic tastes were combined with high- or low-pitched sounds. Sensitivity was found to be significantly higher

when sour items were paired with high-pitched sounds (*d'* = 3.42, *SD* = 0.98) as compared to when they were paired with low-pitched sounds (*d'* = 2.92, *SD* = 0.96, *t*(27) = 3.00, *p* = .006). There was also a significant difference in sensitivity between the names associated with sweet tastes paired with high-pitched sounds (*d'* = 3.46, *SD* = 0.77) and with low-pitched sounds (*d'* = 3.04, *SD* = 0.88, *t*(27) = 3.69, *p* = .001, see Figure 2.3). These results therefore suggest that sweet and sour tastes are associated with high-pitched sounds. No change in sensitivity was found for bitter or salty tastes between the two pairing conditions.



Figure 2.3: Sensitivity (d') for the different tastes paired with high-pitched or low-pitched sounds in Experiment 2.2. Error bars represent the standard errors of the means. ** indicates a significant difference ($p < .01$).

The RT data were also compared between the two pairing conditions for each taste. The participants responded more rapidly when the names of sweet items were paired with high-pitched sounds (*M* = 458 ms, *SD* = 49.8) than when they were paired with low-pitched sounds (*M* = 486 ms, *SD* = 46.9, *t*(27) = 3.86, *p* = .001). The participants also responded more rapidly when the names associated with sour items were paired with high-pitched sounds, although this difference failed to reach statistical significance (*M* = 469 ms, *SD* = 61.1, *M* = 480 ms, *SD* = 47.8, *t*(27) = 1.49, *p* = .149, see Figure 2.4). These results confirm that sweet and sour tastes appear to be associated with high-pitched sounds, as already shown by the *d'* analysis.

Moreover, while not contradicting the results obtained from previous IAT studies, they nevertheless suggest that the sour-high pitch and sweet-high pitch associations were mainly responsible for the IAT effects reported and that there do not seem to be any associations between bitter-low pitch and salty-low pitch.

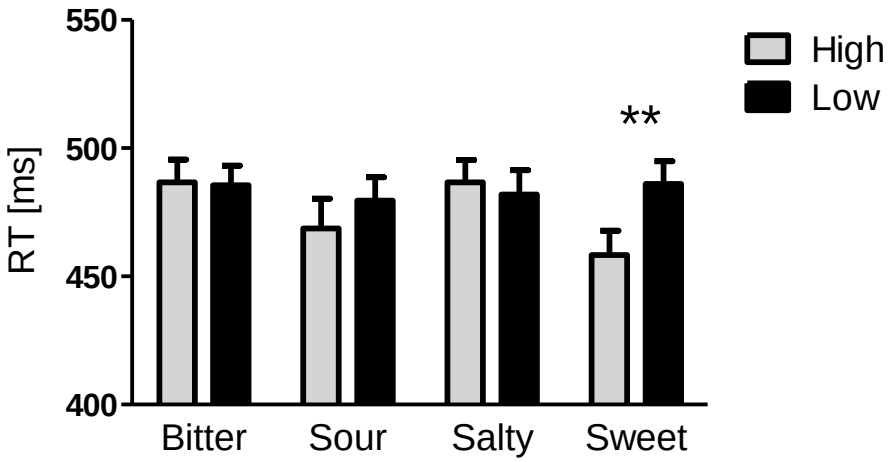


Figure 2.4: RT for the different tastes paired with high-pitched or low-pitched sounds in Experiment 2.2. Error bars represent the standard errors of the means. ** indicates a significant difference ($p < .01$).

A repeated measures ANOVA, with Greenhouse-Geisser correction, was conducted in order to assess whether pleasantness ratings varied between the four basic tastes. The results indicated that the ratings did vary as a function of taste ($F(2.27, 61.31) = 17.00$, $p < .001$). Post-hoc *t*-tests (Bonferroni-corrected) revealed that all pairs of tastes were significantly different from each other (at $p < .05$), with the exception of bitter and sour (see Table 2.3).

Table 2.3: Pleasantness ratings for the items in the four taste categories in Experiment 2.2.

Taste	Mean pleasantness rating	Standard error
Bitter	4.94	.33
Salty	6.20	.27
Sour	5.13	.29
Sweet	7.39	.26

Gender, first language (English vs. other), nationality (British vs. other), and practice of a musical instrument had no effect on the difference in sensitivity between the two pairings condition for any of the tastes (independent-samples *t*-tests).

2.3.3 Discussion

The results of Experiment 2.2 confirmed the existence of crossmodal associations between both sour and sweet tastes and high pitch. However, it also suggested that there were no associations between either bitter or salty tastes and low pitch. The pairings observed in Experiment 2.1 would have thus been mainly driven by the associations with high pitch.

One potential dimension that could drive these associations is pleasantness, as mentioned in Experiment 2.1. While it could explain the association between sweetness and high pitch, as sweet items were rated as more pleasant than all the other items, it fails to satisfactorily explain the association between sourness and high pitch, as sour items were not rated as significantly more pleasant than bitter items, and were, in fact, rated as significantly less pleasant than salty items.

One issue with the use of names of food items instead of gustatory stimuli is that they can lead to important between-participants differences. For instance, the name *beer* can refer to a wide range of beverages, all having distinctive tastes (some more or less bitter than others). This might have led some participants to consider some items as not very representative of the taste

category they belonged to, or even to disagree with the classification altogether (although remember a pilot survey was used to select the bitter and sour items). As a control for this last possibility, participants were asked to rate the similarity of all stimulus pairs in Experiment 2.3, and subjected the results to a multidimensional scaling analysis, to see if the stimuli would form four distinct categories corresponding to the basic tastes.

2.4 Experiment 2.3

2.4.1 Methods

2.4.1.1 Participants

20 new participants took part in Experiment 2.3 (13 females, aged 19-32 years). The experiment took about 15 minutes and participants were compensated for their time by a £5 (UK Sterling) gift voucher.

2.4.1.2 Stimuli

The 20 names of foods and drinks used in Experiments 2.1 and 2.2 were also used here (see Table 2.1), with the exception of the two non-food neutral stimuli (spoon and fork).

2.4.1.3 Procedure

Participants were asked to rate the similarity in terms of taste of the 153 pairs of food/drink items on a 7-point scale, anchored by *very dissimilar* and *very similar*. The pairs were presented on a 60 Hz refresh rate LCD monitor in a random order, using the programme E-Prime. Participants were free to take as much time as needed to make their choice, but were made aware of the approximate number of pairs to be rated.

2.4.1.4 Data analysis

The average dissimilarity measure for each pair of items was used to conduct a multidimensional scaling (MDS) analysis, using the PROXSCAL module available in SPSS. Ordinal MDS was chosen, and solutions were computed for 1 to 4 dimensions.

2.4.2 Results and discussion

The scree plot revealed a big improvement from 1D to 2D (normalized raw stress decreasing from .25 to .06), but then not much improvement when more dimensions were added (.06 to .025).

The 2D representation shows that the four groups representing the four basic tastes are clearly separated (see Figure 2.5), thus justifying our use of these items to represent basic taste categories. There seem to be a salty-sweet axis and a bitter-sour axis. The choice of 'neutral' stimuli seems not to have been very good, bread being very close to the salty stimuli. The bitter stimuli are, unsurprisingly, the most spread out. This might explain why the association between bitter and low pitch, which was hypothesised from the results of Experiment 2.1, was surprisingly not confirmed in Experiment 2.2. As most bitter items used also had a sweet component (beer, coffee, dark chocolate), the associations between sweetness and high pitch might have affected the participants' performance with bitter items.

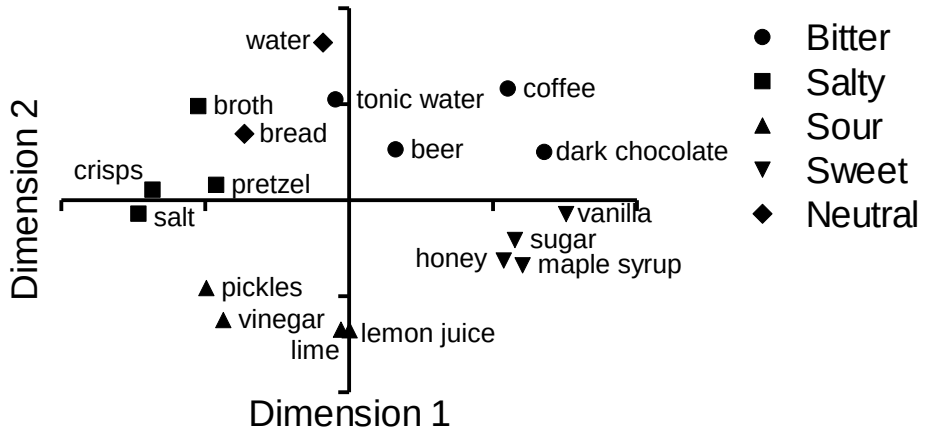


Figure 2.5: MDS solution in 2D from Experiment 2.3.

2.5 General discussion

At the time that this study was conducted, these results showed for the first time the existence of implicit associations between basic tastes and the pitch of musical notes. Sour and sweet tastes were consistently associated with high pitch. Bitter and salty tastes were

associated with lower pitch than sour and sweet in Experiment 2.1, but failed to elicit an association with low pitch when considered on their own in Experiment 2.2.

The low incidence of taste-sound synaesthesia (Pierce, 1907; only 30 out of 572 cases of synaesthesia reported by Day, 2005; no mention by Novich, Cheng, & Eagleman, and only 8% of all their reported cases are sound-taste synesthesia) essentially rules out the possibility that these results were caused by a few of the participants experiencing synaesthesia. Corroboration for this suggestion comes from the fact that none of the participants self-reported any kind of synaesthetic experience. Moreover, it should also be remembered that all of the tastes in the present study were evoked by the names of food and drinks and not by actual tastants.

These results suggest a possible mechanism for Holt-Hansen's results (1968). The two varieties of beer used in Holt-Hansen's original study might have varied in their basic taste levels, thus being associated with sounds of different pitches. This explanation would be in accordance with the reported crossmodal associations between beer and shapes (Deroy & Valentin, 2011). However, it is important to note, once again, that, in the experiments reported here, the names of foods (instead the foods themselves) were used.

Indeed, the use of names of foods raises a number of issues. First, it introduces between-participant differences, depending on their experience with the food items in question (e.g., coffee with sugar or milk, types of beers). This, combined to the choice of food items, might lead to some items constituting better exemplars of their category than others. One way to reduce this problem could have been to present each food item before the experiment to act as a reference. Second, the shape of the letters and the phonemes of the names themselves might have induced associations of their own (Ngo, Misra, & Spence, 2011; Simner, Cuskley, & Kirby, 2010). Third, no gustatory stimuli were actually presented thus preventing the study of possible perceptual interactions between the sensory modalities.

This leads us to the level at which these crossmodal associations occur. The associations could not have occurred at the perceptual level in these experiments as no gustatory stimuli

were presented. They must thus have occurred at some higher, possibly semantic level. Finding a similar dimension associated with both pitch and basic tastes might help explaining how these associations are formed. One candidate was pleasantness: It is both commonly used as a dimension in IAT studies and in studies dealing with tastes. However, while high pleasantness might be associated with high pitch in the case of sweetness, this explanation does not hold for other tastes such as bitterness and sourness, which are, respectively, associated to no particular/low pitch and high pitch, even though their pleasantness ratings are similar. Another possible concept linking tastes and sounds could be the signalling of danger. It is one of the major functions of taste: Many natural poisons have a bitter taste (Garcia & Hankins, 1975), and sourness signals a low pH, thus signalling products that should not be ingested. High-pitched sounds can be associated with various types of alarms. However, it has been shown that neurocognitively normal individuals tend to associate low-pitched sounds with large objects (Gallace & Spence, 2006; see Spence, 2011, for a review). Low-pitched sounds can thus also signal danger (such as the proximity of a large truck or a large predator, for example). An association between various types of danger signals might be advantageous, but this would not explain the specific associations between tastes and pitch, as bitterness, sourness, high pitch, and low pitch could all be associated with danger. At this point, it is thus difficult to hypothesise on a concept or dimension that could drive the associations uncovered in Experiment 2.1 and 2.2. Moreover, cultural factors (first language, country of origin), and musical experience seem not to affect these associations, although it should be noted that the measures used were very crude.

The limitations of these first experiments point to the direction(s) for further research. The use of real gustatory stimuli (in place of names of food items) is explored in Chapter 3. The experiments reported in the next chapter also explore whether the taste-pitch associations still hold when participants are asked explicitly about them. A second dimension of sound, timbre, is added in all subsequent experiments reported in this thesis. Hypotheses concerning the

subtending dimension(s) of the associations are developed through the use of principal component analysis in Chapter 3. Two such dimensions, the pleasantness of stimuli and the expertise of participants, are explored in more details in Chapter 4.

3 Chapter 3: Explicit associations between chemosensory stimuli and musical notes

3.1 Introduction

The aim of the experiments reported in the present chapter was to confirm the existence of crossmodal associations between chemosensory stimuli and sounds when gustatory or olfactory stimuli are presented instead of their names. A wide range of different stimuli were tested: basic taste solutions (Experiment 3.1), flavoured solutions (Experiment 3.1), flavoured milk solutions (Experiment 3.2), crisps (potato chips; Experiment 3.3), and orthonasal odours (Experiment 3.4). The range of sounds used was also extended, offering participants the choice between 13 different pitches, played by four different types of musical instruments. In order to uncover potential factors driving the crossmodal associations, participants were also required to rate the stimuli on a number of dimensions. These ratings were then used to conduct principal component analyses (PCA).

Another difference with the experiments reported in the previous chapter was that the participants were asked explicitly about the crossmodal associations. This allowed participants to choose from a wide range of different sounds, rather than simply comparing their performance between low and high pitch. A similar approach has been used in previous research to explore a number of crossmodal associations that involve chemosensory stimuli: pitch and odours (Belkin et al., 1997), colours and odours (Demattè, Sanabria, & Spence, 2006; Gilbert, Martin, & Kemp, 1996; Schifferstein & Tanudjaja, 2004), and even abstract symbols and odours (Seo et al., 2010).

Experiment 3.1 was designed to replicate the findings of Experiment 2.1 and 2.2 with basic tastes. Participants were thus presented with basic taste solutions. Flavour solutions were also presented to compare the crossmodal associations they might elicit to those elicited by

basic tastes. Experiment 3.2 moved to more complex chemosensory stimuli (flavoured milk solutions). The impact of two factors on any crossmodal associations observed was examined: flavour and fat content. More ecologically valid stimuli were used in Experiment 3.3 (crisps). This experiment investigated whether the multisensory imagery used on product packaging corresponds to the crossmodal associations that occur naturally in UK consumers. Finally, Experiment 3.4 studied crossmodal associations between odours and musical notes. Such associations have been explored previously (Belkin et al., 1997), but with odours used in perfumery. In Experiment 3.4, odours commonly found in wine were used so that the results can be compared to those obtained with tastes and flavours.

3.2 Experiment 3.1

3.2.1 Methods

3.2.1.1 Participants

34 participants took part in Experiment 3.1 (20 females, aged 20-37 years). The experiment was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their senses of smell and taste, and no hearing impairment. They were instructed not to have any meal, coffee, or to smoke in the 30 minutes prior to taking part in the study. The experiment lasted for approximately 40 minutes and the participants were compensated for their time with a £5 (UK Sterling) gift voucher. A subset of 17 participants (12 females, aged 20-34 years) also took part in the second part (on a separate day).

3.2.1.2 Stimuli

The 12 gustatory stimuli were chosen to represent the five basic tastes (caffeine - bitter, citric acid - sour, sucrose - sweet, sodium chloride - salty, and monosodium glutamate, MSG - umami) as well as a number of more complex flavours (almond, coffee, lemon, orange flower, peppermint, rose, and vanilla). A pilot experiment was conducted on 6 participants in order to approximately match the subjective intensity of the 12 stimuli (see Table 3.1 for details of the

concentrations and compositions of the stimuli used, all compounds were diluted in deionised water). Each sample consisted of 10 ml of one of the solutions, presented in a 200 ml white plastic cup. The samples were identified by a number written on the cup.

Table 3.1: Concentration and composition of the gustatory/flavour stimuli in Experiment 3.1.

Stimuli	Origin	Composition	Concentration (% weight)
Caffeine	Sigma-Aldrich	$C_8H_{10}N_4O_2$	0.15
Citric acid	BDH laboratory supplies	$C_6H_8O_7 \cdot H_2O$	0.10
Sucrose	Silverspoon	$C_{12}H_{22}O_{11}$	8.00
Salt	Saxa	NaCl, sodium hexacyanoferrate II	0.45
MSG	Sigma-Aldrich	$C_8H_8NNaO_4 \cdot xH_2O$	2.00
Almond	Silverspoon	Sunflower oil, extract of almond	2.00
Coffee	Marks & Spencer	Water, alcohol (35%), coffee extracts (25%)	1.00
Lemon	Marks & Spencer	Ethyl alcohol (85%), oil of lemon (10%), water	2.00
Orange flower	Marks & Spencer	Propylene glycol-ethylalcohol (40%), orange oil (1.5%), natural flavours	2.00
Peppermint	Silverspoon	Ethanol, water, flavouring	0.25
Rose	Marks & Spencer	Propylene glycol, alcohol (40%), rose oil (2%), natural flavours	1.50
Vanilla	Silverspoon	Water, ethanol, extract of vanilla	10.00

The auditory stimuli came from an online musical instrument samples database from the University of Iowa Electronic Music Studios (http://theremin.music.uiowa.edu/MIS.html, downloaded on 31/10/09). They consisted of notes played by four types of instruments (piano,

strings, woodwinds, and brass). The pitch of the notes ranged from C2 (64.4 Hz) to C6 (1046.5 Hz) in intervals of two tones. Thus, the participants had a choice of 52 different sounds (13 notes x 4 instruments) to pick from. The sounds were edited to last for 1500 ms, and were presented over closed-ear headphones (Beyerdynamic DT 531) at a loudness of 70 dB (± 1 dB). A subset of 16 notes (C2, E3, G#4, and C6, played by the four types of instruments) was used in the second part of the study.

3.2.1.3 Procedure

The instructions and choice of sounds were programmed in E-Prime. They were presented on a 60 Hz refresh rate LCD monitor. Each trial started with instructions to participants to rinse their mouth with tap water. This instruction remained on the screen for 15 s to ensure a minimum intertrial interval. The participants were then given the number of the sample that they were to taste, and were reminded to take the whole sample (10 ml) into their mouth, keep it in there for a few seconds, and then to expectorate it back into the cup. The participants then had to choose a sound to match the taste. The sounds were presented on 4 scales corresponding to the 4 types of instruments. Pitch increased from left to right. The sounds could be heard by clicking on the scales. The participants were free to click on as many of the sounds as they wished before making their choice. On three occasions, a participant failed to pick a sound for a given taste/flavour. After having chosen, they rated the pleasantness, intensity, complexity, sweetness, sourness, bitterness, and saltiness of the taste/flavour on a separate piece of paper, using linear scales. The pleasantness scale was anchored by *dislike extremely*, *indifference*, and *like extremely*. The complexity scale was anchored by *none* and *extremely complex*. The other scales were anchored by *none* and *extremely strong*. Participants were also asked if they had tasted the same taste/flavour before and could answer *yes*, *no*, or *unsure*. Finally, the participants were asked to identify the taste/flavour if possible. The 12 gustatory stimuli were presented twice in a random order, so that each participant completed a total of 24 trials.

In a second part, half of the participants rated a subset of the sounds on the pleasantness, intensity, and complexity scales. They were also asked to identify the instrument playing if possible.

3.2.2 Results

3.2.2.1 Consistency

When presented with the same taste on the second occasion, participants matched it to exactly the same sound as the first time in 11.3% of the cases on average. This value is significantly different from what would be expected if participants had simply been making a random choice between the 52 possible sounds (1/52 = 1.9%; $t(33) = 5.83$, $p < .001$). This consistency in the pattern of participants' responding was not driven by either pitch or instrument type alone. Both the same pitch and the same type of instrument were matched to a taste presented for the second time significantly more often than expected by chance, respectively in 21.8% (chance level: 7.7%; $t(33) = 7.20$, $p < .001$) and in 41.2% of the cases (chance level: 25%; $t(33) = 5.21$, $p < .001$).

3.2.2.2 Pitch

A repeated-measures ANOVA, with Greenhouse-Geisser correction, was conducted in order to assess whether there were any differences between the average pitch matched to the 12 tastes/flavours. The results indicated that the participants matched the 12 tastes/flavours to pitch differently, $F(7.51, 247.68) = 16.51$, $p < .001$. Following post-hoc *t*-tests (Bonferroni-corrected), the tastes/flavours were assigned to three groups according to the pitch that they were matched to (low, middle, or high, see Figure 3.1), so that tastes/flavours within each group were not significantly different from each other. Moreover, each taste/flavour in the "low" group was significantly different from each taste/flavour in the "high" group.

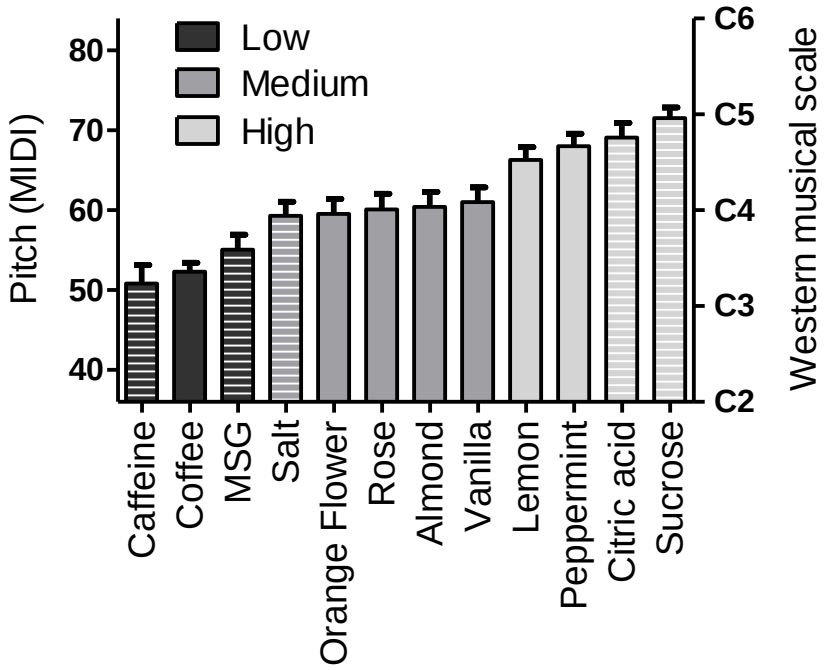


Figure 3.1: Mean pitch matched to each taste/flavour in Experiment 3.1. MIDI (musical instrument digital interface) note numbers were used to code the pitch of the chosen notes. Western musical scale notation is shown on the right-hand y-axis. Basic tastes are depicted with lined bars. Tastes/flavours are grouped into low (dark grey), middle (grey), or high (light grey) groups according to the pitch they were matched to. Error bars represent the SEM.

3.2.2.3 Types of instruments

Chi-square tests for goodness of fit were conducted to determine which tastes/flavours induced a distribution of instrument choice that was different from that expected by chance. Out of the 12 tastes/flavours used, 7 gave rise to significant preferences in the choice of instrument (see Figure 3.2): caffeine ($\chi^2(3, N = 68) = 32.59$, $p < .01$), sucrose ($\chi^2(3, N = 68) = 30.35$, $p < .01$), coffee ($\chi^2(3, N = 67) = 19.39$, $p < .01$), citric acid ($\chi^2(3, N = 68) = 17.53$, $p < .01$), peppermint ($\chi^2(3, N = 68) = 13.65$, $p < .01$), orange flower ($\chi^2(3, N = 68) = 10.00$, $p < .05$), and salt ($\chi^2(3, N = 68) = 9.77$, $p <. 05$). However, it should be noted that, since stimuli were presented twice to each participants, the observations are not equally independent. This violates one of the assumptions of the chi-square test, and these results should be interpreted with caution.

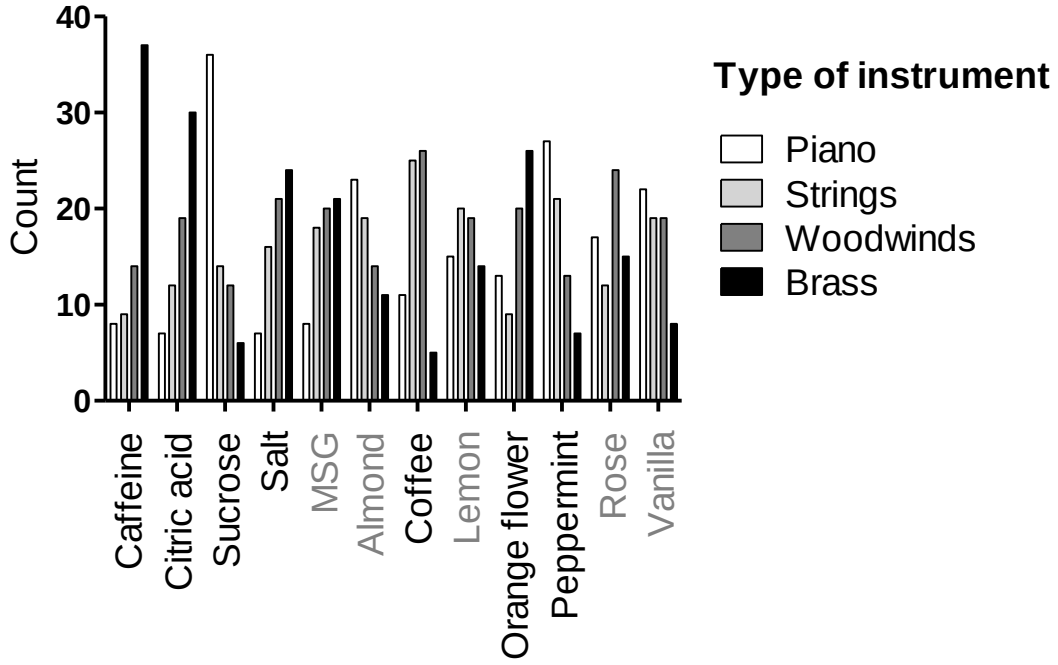


Figure 3.2: Instruments matched to the tastes/flavours in Experiment 3.1. Maximum count is 68 (34 participants, 2 trials for each stimulus). Stimuli for which there were significant preferences in the choice of instrument are highlighted in black.

3.2.2.4 Ratings of tastes/flavours

The majority of the tastes/flavours (10 out of 12) were evaluated as unpleasant (i.e., participants responded using the lower half of the scale, < 50%), the two pleasant stimuli being peppermint (*M* = 57.6%, *SD* = 12.7) and sucrose (*M* = 69.4%, *SD* = 14.0). The mean pleasantness ratings associated with the choice of each instrument were computed for each participant and compared using repeated-measures ANOVAs. The results indicated that the choice of instrument led to significant differences in the pleasantness ratings, $F(3,87) = 56.96$, $p < .001$ (see Figure 3.3a).

A repeated-measures ANOVA, with Greenhouse-Geisser correction, was conducted to check whether there were any differences between the average intensity attributed to the 12 tastes/flavours. Even though a pilot experiment had been conducted to reduce differences in subjective intensity between the stimuli, the results indicated that the participants evaluated the intensity of the 12 tastes/flavours somewhat differently, $F(6.75, 222.75) = 5.36$, $p < .001$.

The mean intensity ratings associated with the choice of each instrument were computed for each participant and compared using repeated-measures ANOVAs. The results indicated that the choice of instrument corresponded to significant differences in the intensity ratings, $F(3,87) = 6.41$, $p = .001$ (see Figure 3.3b).

The mean complexity ratings associated with the choice of each instrument were computed for each participant and compared using repeated-measures ANOVAs. The results indicated that the choice of instrument also led to significant differences in the complexity ratings, $F(3,87) = 3.54$, $p = .018$ (see Figure 3.3c).

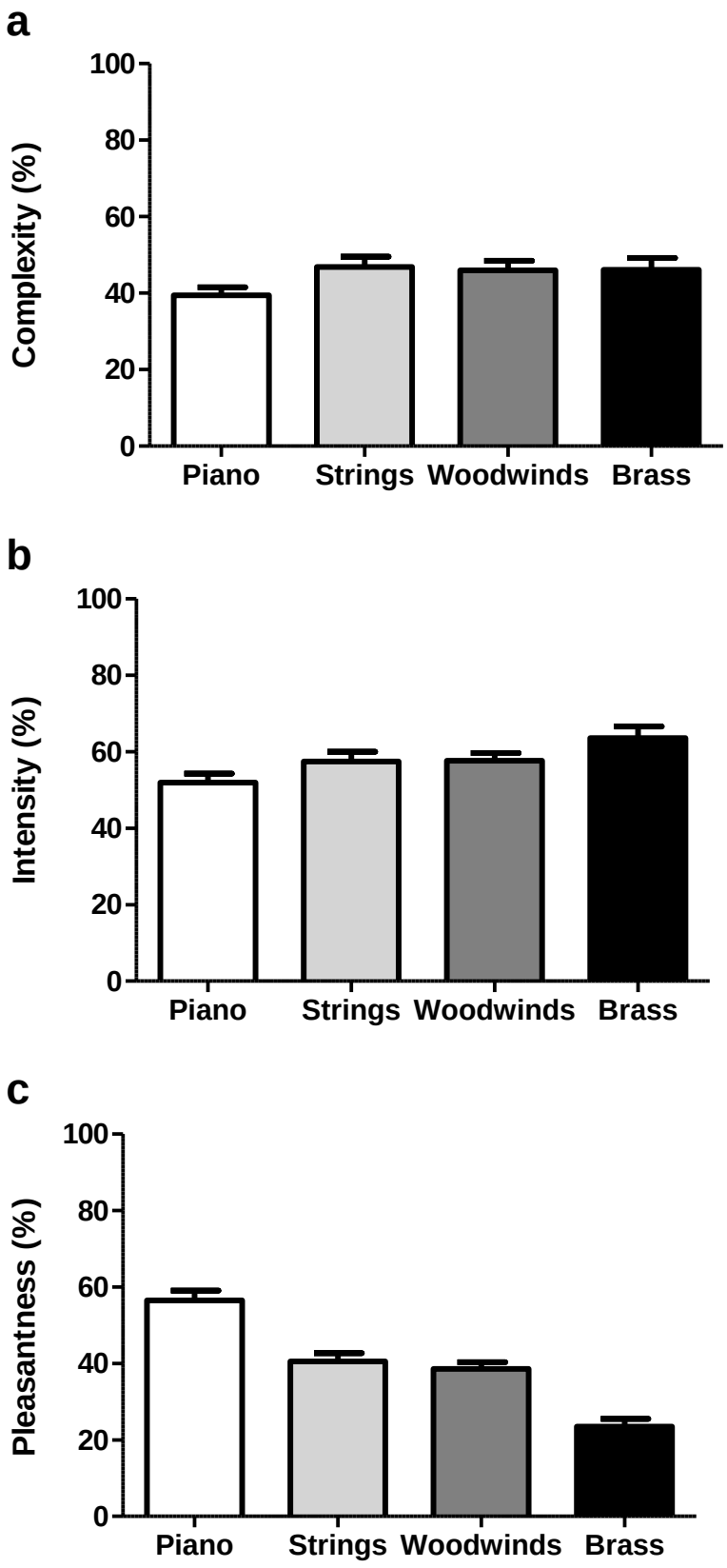


Figure 3.3: Complexity (a), intensity (b), and pleasantness (c) ratings as a function of the choice of instrument in Experiment 3.1. Error bars represent the SEM.

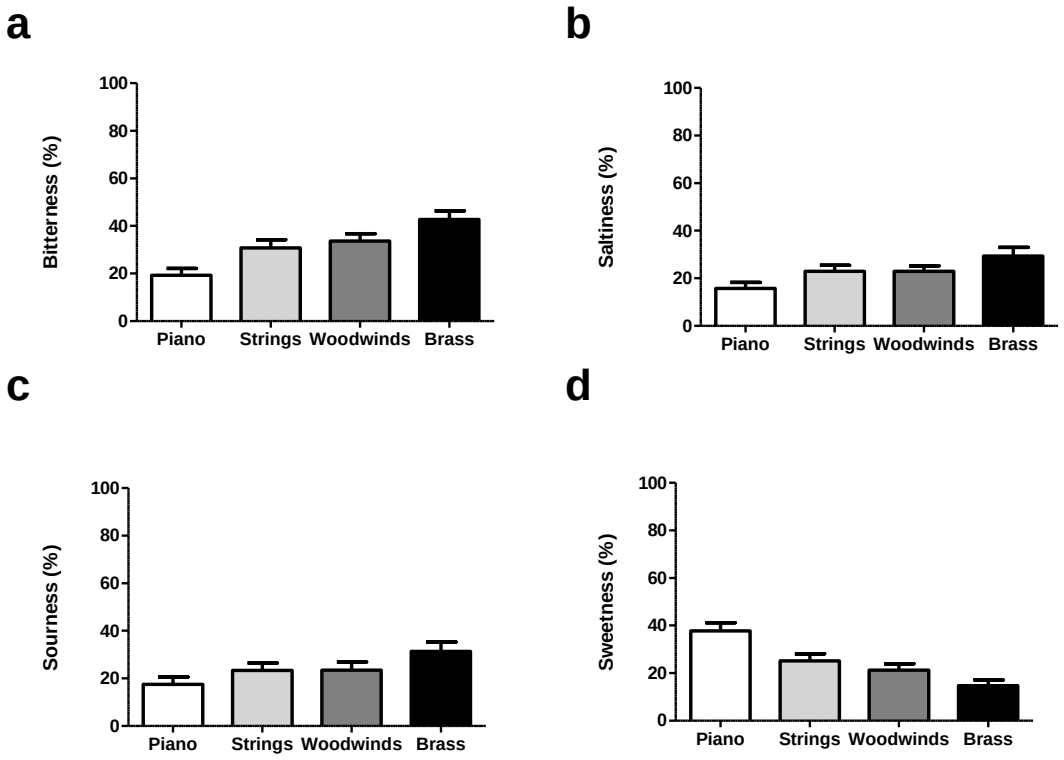


Figure 3.4: Bitterness (a), saltiness (b), sourness (c), and sweetness (d) ratings as a function of the choice of instrument in Experiment 3.1.

Basic tastes ratings varied in function of the choice of instrument, as assessed by repeated-measures ANOVAs (see Table 3.2 and Figure 3.4).

Table 3.2: Average basic taste ratings for different choices of instruments assessed by repeated-measures ANOVAs in Experiment 3.1.

	Instruments					
	piano	**strings**	**woodwinds**	**brass**	**F**	***p***
Bitter	19.54	29.64	35.29	43.95	15.00	< .001
Salty	14.52	22.49	22.37	29.60	6.22	.001
Sour	16.39	23.95	23.89	32.12	6.15	.001
Sweet	37.83	25.19	21.61	13.96	26.80	< .001

A one-way ANOVA revealed that both familiarity with the stimulus and identification of the taste/flavour influenced the choice of pitch, $F(2, 804) = 5.23$, $p < .01$, $F(2, 810) = 24.72$, $p < .001$, respectively (see Figure 3.5).

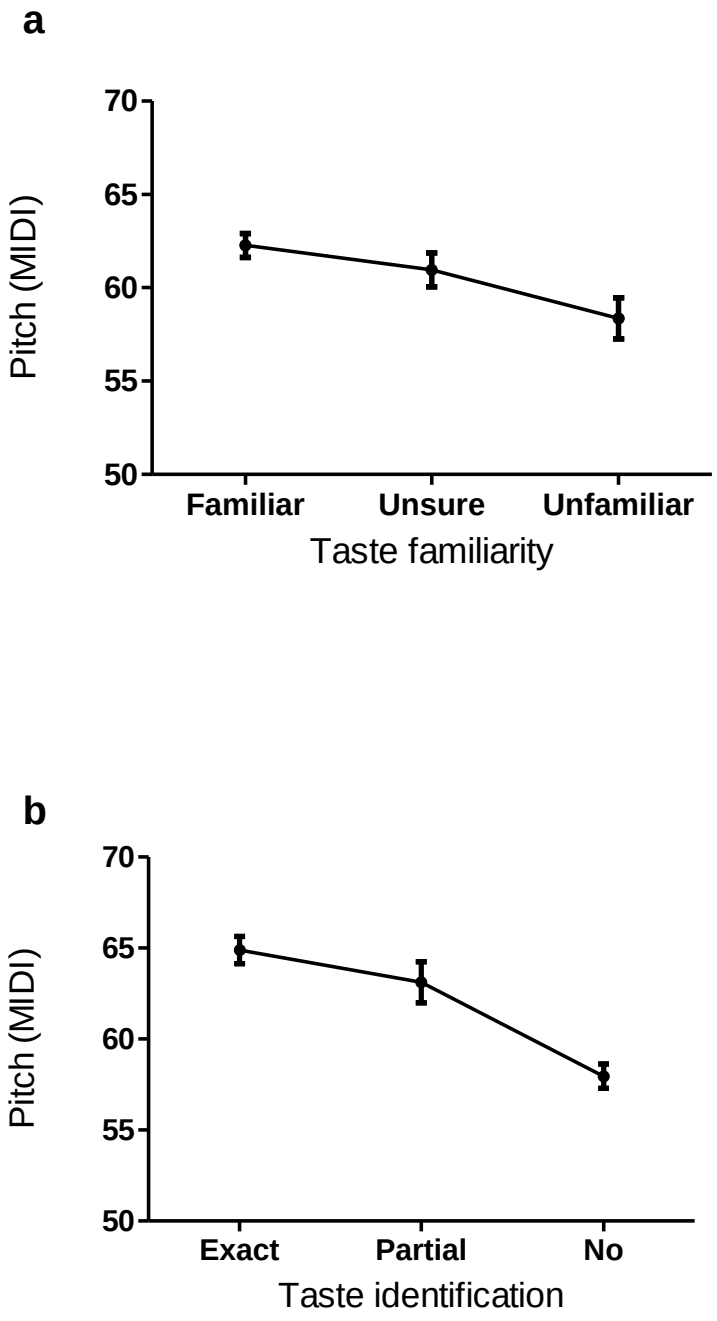


Figure 3.5: Choice of pitch as a function of the familiarity (a) and identification of the taste/flavour (b) in Experiment 3.1. Error bars represent ± 1 SEM.

3.2.2.5 Principal components analysis

The pitch, as well as the seven other ratings (pleasantness, intensity, complexity, sweetness, sourness, bitterness, and saltiness), were subjected to PCA, following the approach suggested by Palland (2005) and using SPSS version 16. The suitability of this approach was assessed first. The correlation matrix revealed the presence of several coefficients above .3. The Kaiser-Meyer-Oklin value was .607, attaining the recommended value of .6 (Kaiser, 1970, 1974), and the Bartlett's test of sphericity (Bartlett, 1954) reached statistical significance, supporting the factorability of the correlation matrix. PCA revealed the presence of three components with eigenvalues over 1, explaining 30.2%, 20.3%, and 13.0% of the variance, respectively. It was decided to keep only two components, based on an inspection of the scree plot, showing a clear break after the second component, and on the results of parallel analysis, which showed only two components with eigenvalues exceeding the corresponding criterion values for a randomly generated data matrix of the same size (8 variables by 408 trials). Varimax rotation was performed. All variables loaded substantially onto only one component, except for bitterness, and, to a lesser extent, pleasantness, which loaded onto the two components (see Figure 3.6). The first component contributed 27.1% of the total variance explained of 50.5%, while the second component contributed 23.4%.

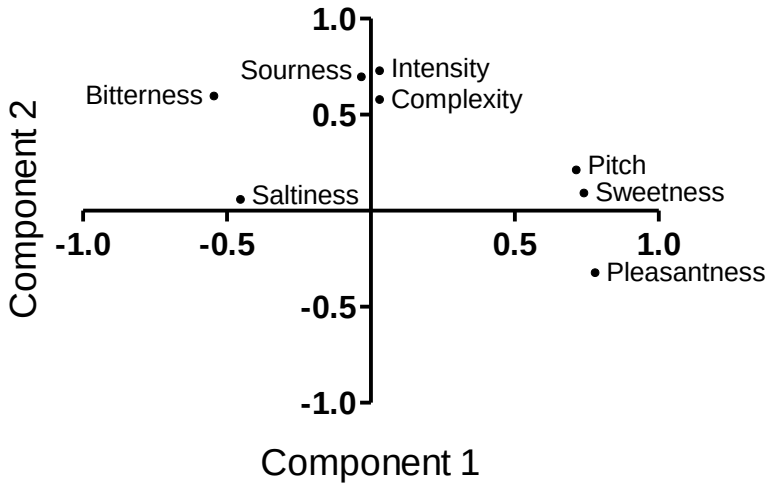


Figure 3.6: Loadings of the pitch and the various ratings on the rotated components extracted through principal component analysis (PCA) in Experiment 3.1.

3.2.2.6 Ratings of sounds

A two-way repeated-measures ANOVA, with Greenhouse-Geisser correction, was conducted to assess the effect of the pitch and the instrument playing the sound on the ratings of pleasantness, intensity, and complexity. The results indicated a significant main effect of the type of instrument on pleasantness ratings, as well as an interaction between type of instrument and pitch, $F(2.69, 43.05) = 65.87$, $p < .001$, $F(5.95, 95.15) = 7.58$, $p < .001$, respectively (see Figure 3.7a). Intensity ratings were influenced by both the pitch and type of instrument, $F(2.27, 34.29) = 11.22$, $p < .001$, $F(2.33, 37.32) = 15.83$, $p < .001$, as well as by the interaction between these two factors $F(6.31, 101.01) = 5.97$, $p < .001$ (see Figure 3.7b). The only significant main effect on the complexity ratings was found for pitch $F(2.30, 36.76) = 12.45$, $p < .001$ (see Figure 3.7c). The instrument playing was correctly identified in 33.1% of the cases, and in a further 27.6%, the type of instrument (e.g., strings) was identified. The piano was recognized in 100% of the cases, whereas brass instruments were only identified exactly in 4.4% of the cases (and in a further 48.5%, participants recognized that is was a wind instrument).

Strings and woodwinds reached intermediate scores (respectively 14.7% and 13.2% of correct identification).

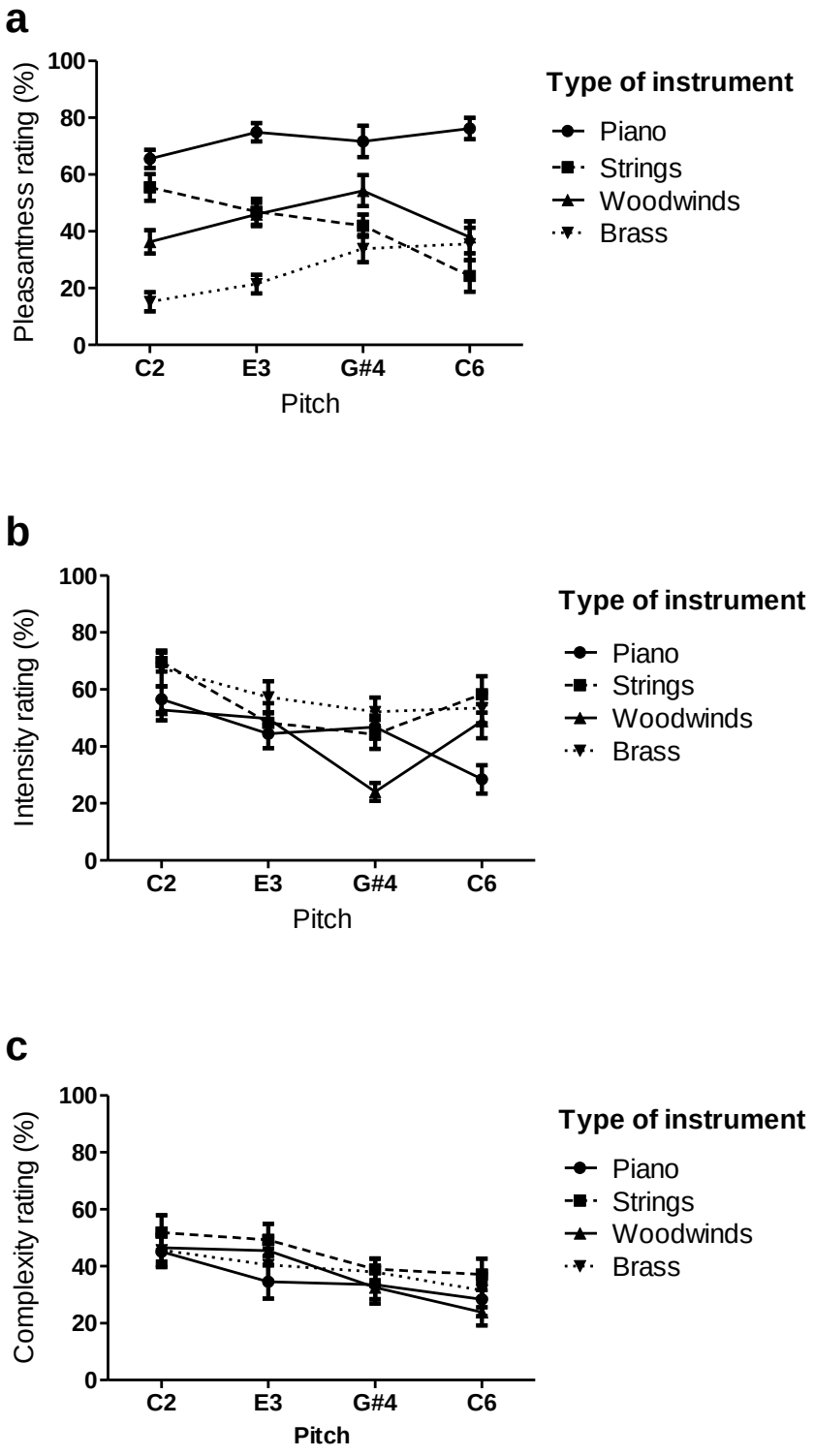


Figure 3.7: Pleasantness (a), intensity (b), and complexity (c) ratings of a subset of the sounds used in Experiment 3.1. Error bars represent the SEM.

3.2.3 Discussion

The consistency in the choice of the sounds matched to each taste/flavour by the participants in Experiment 3.1 confirms the fact that they did not choose randomly. It is unlikely that the consistency observed was due to a memory effect (i.e., the participants trying to be consistent by remembering their first choice), as most of them were unaware that the same stimuli were presented twice. Both the pitch of the sound and the instrument playing it influenced participants' choice.

The choice of the pitch attributed to the basic tastes confirms the results obtained previously in Experiment 2.1 and 2.2 when the names of food or drink items were used instead of actual tastes/flavours. Namely, the present results also show that sour and sweet tastes are preferentially associated with high-pitched sounds. There is also some evidence of a crossmodal association between bitterness and low pitch, which had first been observed in Experiment 2.1, before being discarded when the associations were investigated separately in Experiment 2.2. This association might have been overlooked previously because of the choice of stimuli used to represent the bitter taste in Experiment 2.1 and 2.2 (beer, coffee, dark chocolate, and tonic water), which participants did not agree on unanimously, some of them feeling these were not good exemplars of bitterness. The absence of an association between salty tastes and extreme pitch is also confirmed by the results (at least at the salt intensity used). Moreover, they suggest a possible association between umami and low pitch.

It is further interesting to note that the strongest associations with pitch in this experiment were found for basic tastes rather than for flavours. Four out of seven flavours were classified in the middle group. The presence of the lemon flavour in the high pitch group might be attributable to its high sourness rating (M = 40.6%, SD = 27.6, second after citric acid). The coffee flavour (unsweetened) is traditionally thought of as tasting bitter, which might explain its classification in the low pitch group. However, in this case, the explanation is less convincing than for lemon, since both orange flower and rose flavours were rated as more bitter (M =

42.3%, *SD* = 27.2, *M* = 40.6%, *SD* = 25.5) than the coffee flavour (*M* = 38.7%, *SD* = 25.7). These weaker associations between flavours and pitch are surprising given that odours have been shown to be associated with pitches (Belkin et al., 1997). However, several differences between Belkin et al.'s study and the present experiment might help to explain the contradictory results: Most of the odours used by Belkin et al. were flower or plant odours rather than food odours; the odours were smelled orthonasally, in contrast to the present study, where odours could be smelled both ortho- and retronasally; and the attention of the participants was focused on the odours rather than on the tastes in Belkin et al.'s study.

The classification of the peppermint flavour in the high pitch group suggests a possible crossmodal association between trigeminal stimulation and high pitch. Further research would be needed, exploring other kinds of trigeminal stimuli (e.g., chilli, horseradish) in order to determine whether high pitch is associated to trigeminal stimulation more generally, or only to the perceived coolness of peppermint.

Sounds played by the piano were preferentially chosen for tastes/flavours rated as pleasant; whereas unpleasant tastes were matched most often to sounds played by brass instruments (see Figure 3.3). Brass instruments were also preferred for stimuli rated as tasting very bitter or sour (see Figure 3.4). This tendency corresponds to the pleasantness ratings of the sounds (see Figure 3.7): The piano was rated as most pleasant at all pitches, and the brass instruments as the most unpleasant, especially at lower pitches. This suggests that the choice of the instrument matched to a taste can largely be attributed to a matching of the hedonic values of the two stimuli.

Tastes that the participants reported themselves as being familiar with, or that they could identify correctly, were matched to higher pitched sounds (see Figure 3.5).

PCA suggests two components to account for the various ratings of the tastes, as well as for the pitch matched to the tastes (see Figure 3.6). The first component has strong loadings of

pleasantness and sweetness. The choice of pitch seems related to this component. The second component has a strong loading of the intensity factor, as well as of sourness, bitterness, and complexity. These two components might correspond to the first two (evaluation and potency) of the dimensions found in the semantic differential method (Osgood, 1952; Osgood et al., 1957) that has been applied to a variety of stimuli, and recently to odours (Dalton et al., 2008). The third dimension, activity, might be linked to the time-course of the perception of taste, which is itself influenced by parameters that were not varied in this experiment, such as the texture of the stimuli.

Given that similar results were also obtained when tastes were evoked by names of food items in Experiments 2.1 and 2.2, the crossmodal associations must occur at a higher cognitive level, as suggested by Martino and Marks's (1999) semantic coding hypothesis.

3.3 Experiment 3.2

3.3.1 Methods

3.3.1.1 Participants

22 participants took part in Experiment 3.2 (13 females, aged 18-55 years). The experiment was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their senses of smell and taste, and no hearing impairment. They were instructed not to eat, drink coffee, or smoke in the 30 minutes prior to taking part in the study. The experiment lasted for approximately 40 minutes and the participants were compensated for their time with a £5 (UK Sterling) gift voucher. A subset of 12 participants (7 females, aged 20-36 years) also took part in the control experiment.

3.3.1.2 Stimuli

The 16 gustatory stimuli were presented using a 4x4 experimental design: four flavour conditions (lemon, orange flower, vanilla, or no added flavour) were presented in four types of milk (pasteurised and homogenised, Sainsbury's) varying in their fat content: skimmed (0.1% fat), low-fat (1% fat), semi-skimmed (2% fat), and whole milk (4% fat). Table 3.3 gives the details of the compositions and concentrations used. Each sample consisted of 10 ml of one of the solutions, presented in a 200 ml white plastic cup. The samples were identified by a number written on the cup.

For the control experiment, pairs of unflavoured milk samples of varying fat content were presented in the same way. All possible combinations of types of milk were presented once in a random order.

The auditory stimuli were the same as in Experiment 3.1.

Table 3.3: Concentration and composition of the flavoured solutions in Experiment 3.2.

Stimuli	Origin	Composition	Concentration (wt/wt)
Lemon	Marks & Spencer	Ethyl alcohol (85%), oil of lemon (10%), water	2.0
Orange flower	Marks & Spencer	Propylene glycol-ethylalcohol (40%), orange oil (1.5%), natural flavours	2.0
Vanilla	Silverspoon	Water, ethanol, flavouring	10.0

3.3.1.3 Procedure

Each trial started with instructions to participants to rinse their mouth with tap water. This instruction remained on the screen for 15 s to ensure a minimum intertrial interval. The participants were then given the number of the sample that they were to taste, and were reminded to take the whole sample (10 ml) into their mouth, keep it in there for a few seconds, and then to spit it back into the cup. Next, the participants had to choose a sound to match the taste. The sounds were presented on four scales corresponding to the four types of instruments. Pitch increased along the scales (horizontally), the direction was randomly chosen for each trial. The sounds could be heard by clicking on the scales. The participants were free to click on as many of the sounds as they wished before making their choice. After having chosen, they rated the pleasantness, intensity, complexity, sweetness, sourness, bitterness, saltiness, and familiarity of the sample on 9-point scales. The scales were presented in a random order, excluding potential confounds from order or spatial position effects. The pleasantness scale was anchored by *extremely unpleasant* and *extremely pleasant*. The complexity scale was anchored by *none* and *extremely complex*. The familiarity scale was anchored by *not familiar at all* and *extremely familiar*. The other scales were anchored by *none* and *extremely strong*. Finally, the

participants had to try and identify the sample. The 16 gustatory stimuli were presented in a random order.

In the control experiment, a subset of the participants tasted 10 pairs of unflavoured milk samples and had to detect whether they were identical or not. The participants were informed that only the fat content would vary.

3.3.2 Results

3.3.2.1 Pitch

A repeated-measures ANOVA was conducted in order to assess whether either the added flavours or the fat content of the milk had an effect on the pitch chosen to match the samples. The results indicated that while the flavours had an effect ($F(3, 63) = 7.45$, $p < .001$), neither the fat content ($F(3, 63) = 1.02$, $p = .39$), nor the interaction between the two factors did ($F(9, 189) = 1.14$, $p = .34$). Post-hoc *t*-tests (Bonferroni-corrected) revealed that the differences in chosen pitch between the lemon and vanilla flavours ($p = .005$), as well as between the orange flower and vanilla flavours ($p = .01$) were significant (see Figure 3.8).

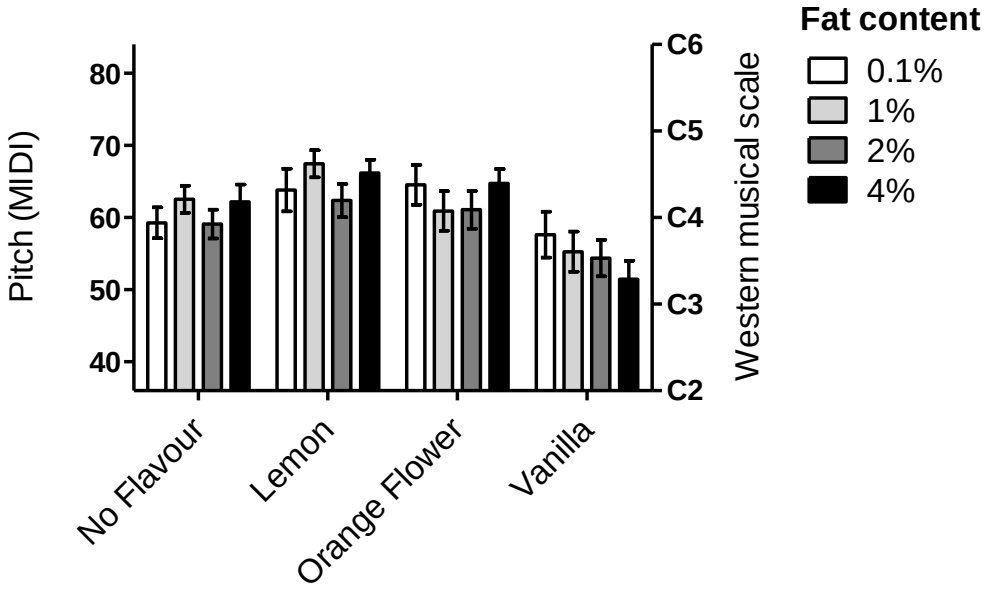


Figure 3.8: Mean pitch matched to each flavour and fat content. MIDI note numbers were used to code the pitch of the chosen notes in Experiment 3.2. Western musical scale notation is shown on the right-hand y-axis. Error bars represent the SEM.

3.3.2.2 Types of instruments

Chi-square tests for goodness of fit were conducted in order to determine which conditions induced a distribution of instrument choice that was different from that expected by chance. Out of the 16 conditions, four gave rise to significant preferences in the choice of instrument: 2% fat milk with lemon ($\chi^2(3, N = 22) = 8.18$, $p = .042$), 4% fat milk with no added flavour ($\chi^2(3, N = 22) = 18.36$, $p < .001$), 2% fat milk with no added flavour ($\chi^2(3, N = 22) = 11.82$, $p = .008$), and 1% fat milk with no added flavour ($\chi^2(3, N = 22) = 10.73$, $p = .013$). For one more condition, 0.1% fat milk with no added flavour, the result was marginally significant, $\chi^2(3, N = 22) = 7.46$, $p = .059$. It thus seems that the flavour of the milk itself was associated with a preference for the piano, while the fat content of the milk did not affect the choice of instrument (see Figure 3.9).

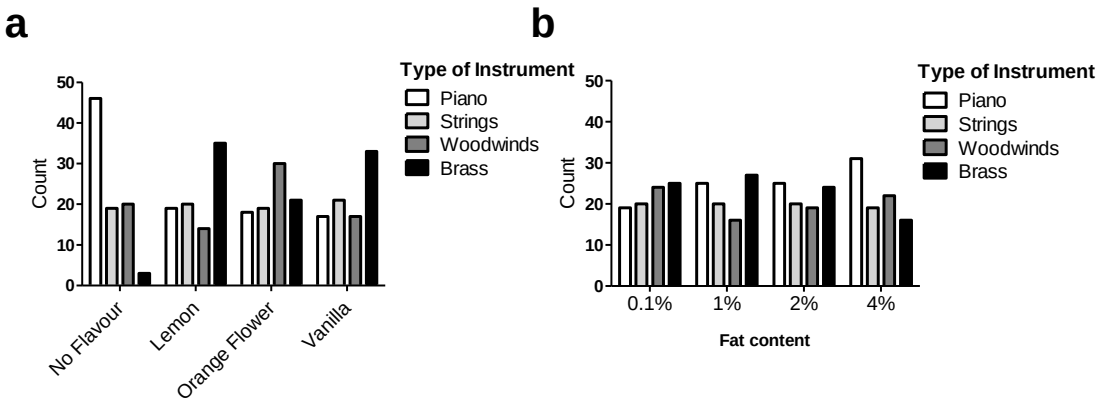


Figure 3.9: Instrument types matched to the stimuli in Experiment 3.2. Instruments matched to each flavour (a), and each level of fat content (b). Maximum count is 88 (22 participants, 4 fat conditions for each flavour, and vice-versa).

3.3.2.3 Pleasantness

A repeated-measures ANOVA was conducted in order to assess whether either the added flavours or the fat content of the milk had an effect on the pleasantness ratings. The results indicated that both flavours ($F(3, 63) = 23.91$, $p < .001$) and fat content ($F(3, 63) = 9.90$, $p = .001$) had an effect, but there was no interaction between these two factors ($F(9, 189) = 1.40$, $p = .19$; see Figure 3.10a). The mean pleasantness ratings associated with the choice of each instrument

were computed for each participant and compared by using repeated-measures ANOVAs. The results indicated that the choice of instrument led to significant differences in the pleasantness ratings, F(3,48) = 20.55, $p < .001$ (see Figure 3.11a).

3.3.2.4 Intensity

A repeated-measures ANOVA was conducted in order to assess whether either the added flavours or the fat content of the milk had an effect on participants' intensity ratings. The results indicated that both flavours ($F(3, 63) = 39.71$, $p < .001$), and fat content ($F(3, 63) = 6.46$, $p = .001$) had an effect, but the interaction between the two factors was not significant ($F(9, 189) = 1.40$, $p = .08$; see Figure 3.10b). The reduction in ratings of flavour intensity with increasing fat content could have resulted from a reduction in the release of lipophilic compounds (see Roberts, Pollien, Antille, Lindinger, & Yeretzian, 2003).

3.3.2.5 Complexity

The complexity ratings were compared to those obtained in Experiment 3.2. As expected, the perceived complexity was higher in the present study, $t(758) = -2.38$, $p = .02$. A repeated-measures ANOVA was conducted in order to assess whether either the added flavours or the fat content of the milk had an effect on complexity ratings. The results indicated that while the flavours had an effect ($F(3, 63) = 34.76$, $p < .001$), neither the fat content ($F(3, 63) = 2.25$, $p = .09$), nor the interaction between the two factors did ($F(9, 189) = .72$, $p = .69$; see Figure 3.10c). Post-hoc *t*-tests (Bonferroni-corrected) revealed that only the difference between orange flower and vanilla flavours failed to reach statistical significance. The mean complexity ratings associated with the choice of each instrument were computed for each participant and compared by using repeated-measures ANOVAs. The results indicated that the choice of instrument led to significant differences in the complexity ratings, F(3,48) = 3.41, $p = .025$.

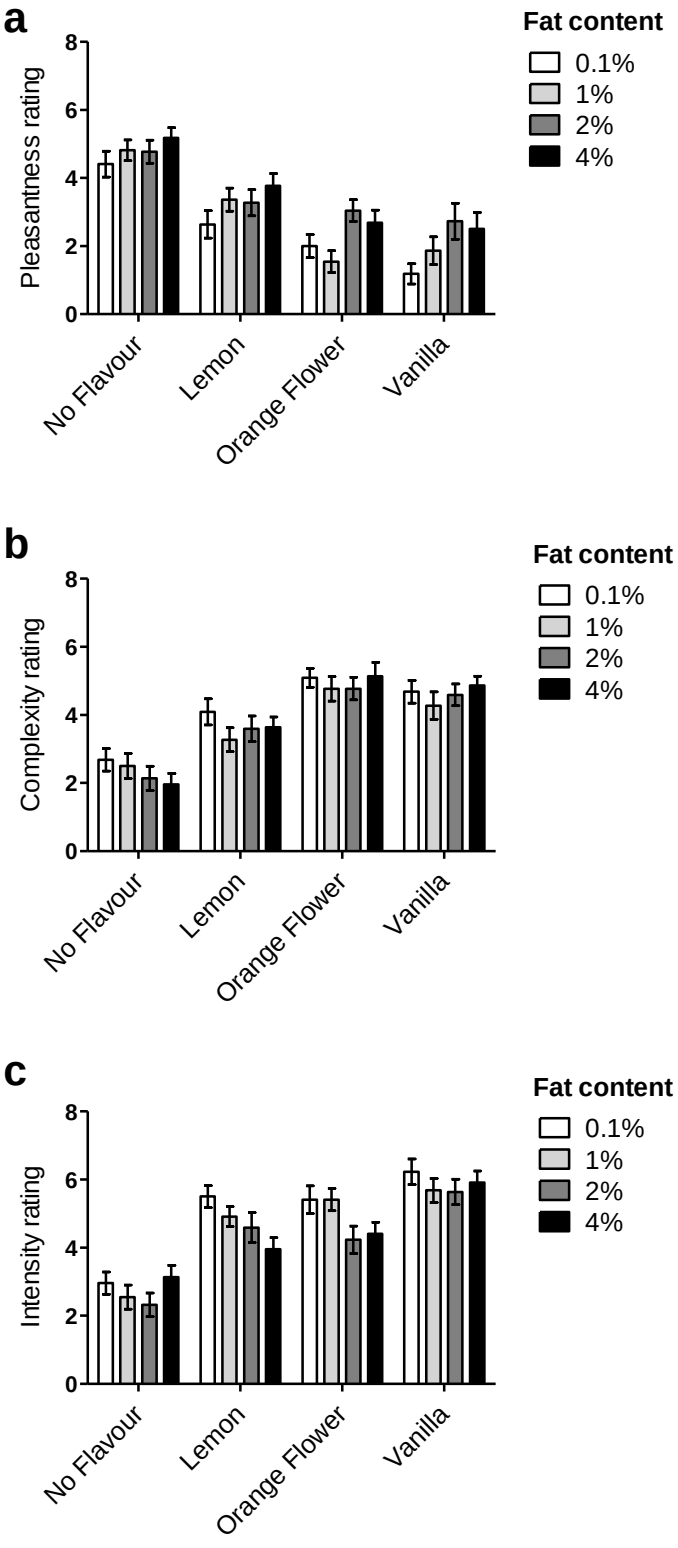


Figure 3.10: Ratings for pleasantness (a), intensity (b), and complexity (c) (on a 0-8 scale) as a function of the flavour and fat content of the stimuli in Experiment 3.2. Error bars represent the SEM.

3.3.2.6 Basic tastes ratings

Basic tastes ratings varied as a function of the choice of instrument, as assessed by repeated-measures ANOVAs (see Table 3.4 and Figure 3.12c-f).

Table 3.4: Basic taste ratings for different choices of instruments assessed by repeated-measures ANOVAs in Experiment 3.2.

	Instruments					
	piano	**strings**	**woodwinds**	**brass**	**F**	***p***
Bitter	1.66	3.08	3.07	4.41	8.65	< .001
Salty	0.81	1.53	1.21	1.45	2.65	.059
Sour	2.03	2.57	2.72	4.29	8.56	< .001
Sweet	4.20	3.39	3.13	2.61	4.18	.010

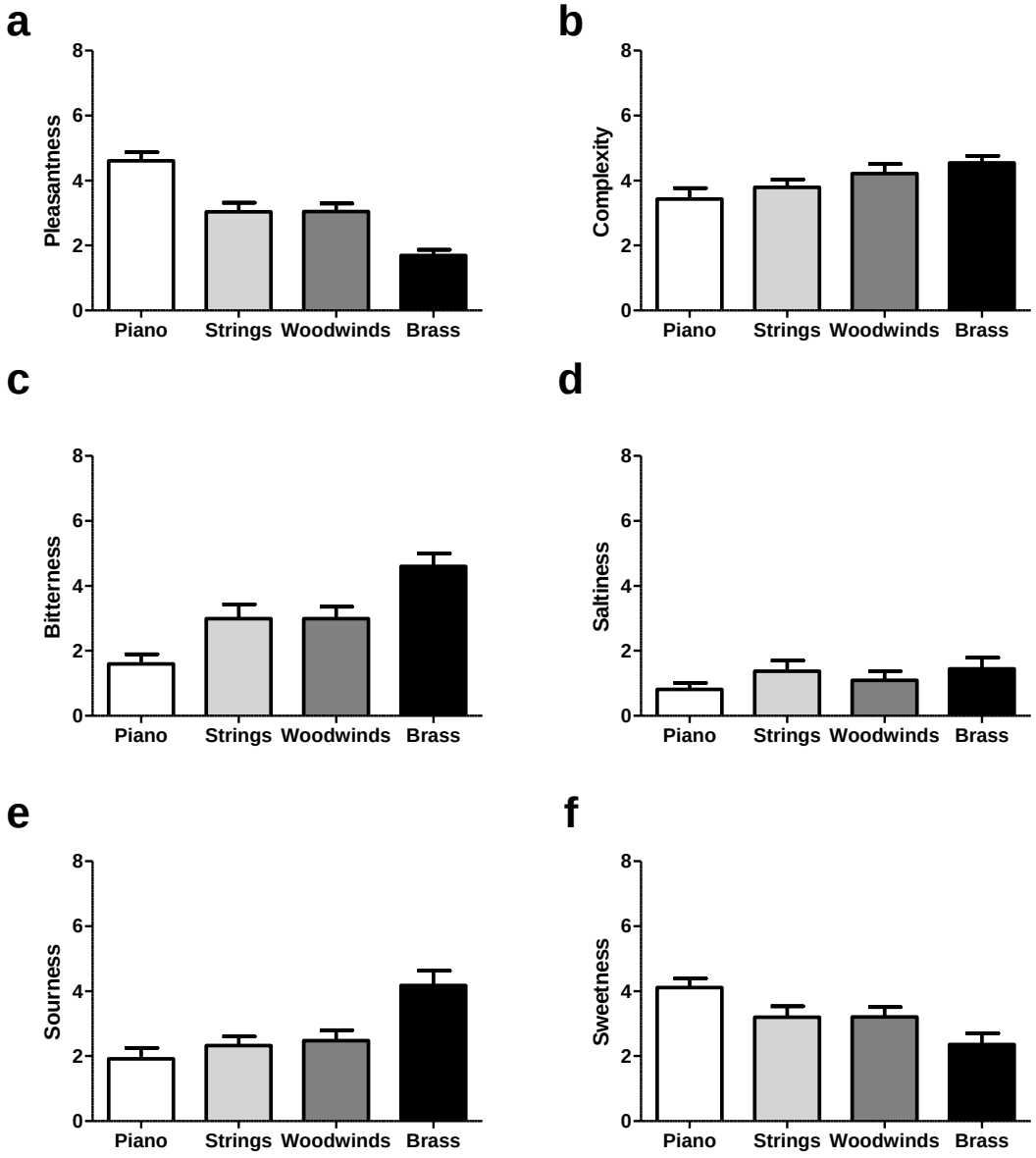


Figure 3.11: Pleasantness (a), complexity (b), bitterness (c), saltiness (d), sourness (e), and sweetness (f) ratings, as a function of the choice of instrument in Experiment 3.2. Error bars represent the SEM.

3.3.2.7 Principal components analysis

In order to investigate how the various ratings and the choice of pitch correlated to each other, and whether they could be reduced to fewer dimensions, the pitch, as well as the 8 other ratings (pleasantness, intensity, complexity, familiarity, sweetness, sourness, bitterness, and saltiness), were subjected to PCA. The suitability of this approach was assessed first. The correlation matrix revealed the presence of several coefficients above .3. The Kaiser-Meyer-

Oklin value was .77, attaining the recommended value of .6 (Kaiser, 1970, 1974), and the Bartlett's test of sphericity (Bartlett, 1954) reached statistical significance, supporting the factorability of the correlation matrix. PCA revealed the presence of three components with eigenvalues over 1, explaining 37.5%, 14.5%, and 12.7% of the variance, respectively. We decided to keep these three components, based on the results of parallel analysis, which showed three components with eigenvalues exceeding the corresponding criterion values for a randomly generated data matrix of the same size (9 variables by 352 trials). Varimax rotation was performed. The first component contributed 34.8% of the total variance explained of 64.7%, while the second and third components contributed respectively 15.3% and 14.6% (see Figure 3.12). The first component has a strong loading of all factors, except for saltiness and pitch. The opposite loadings of bitterness, intensity, sourness, and complexity on the one hand, and pleasantness, sweetness and familiarity on the other, seem to link it to the hedonic evaluation of the stimuli. The second component has strong loadings of pitch and familiarity, as well as sourness and pleasantness. Finally, the third component has strong loadings of saltiness, complexity, sweetness, and familiarity.

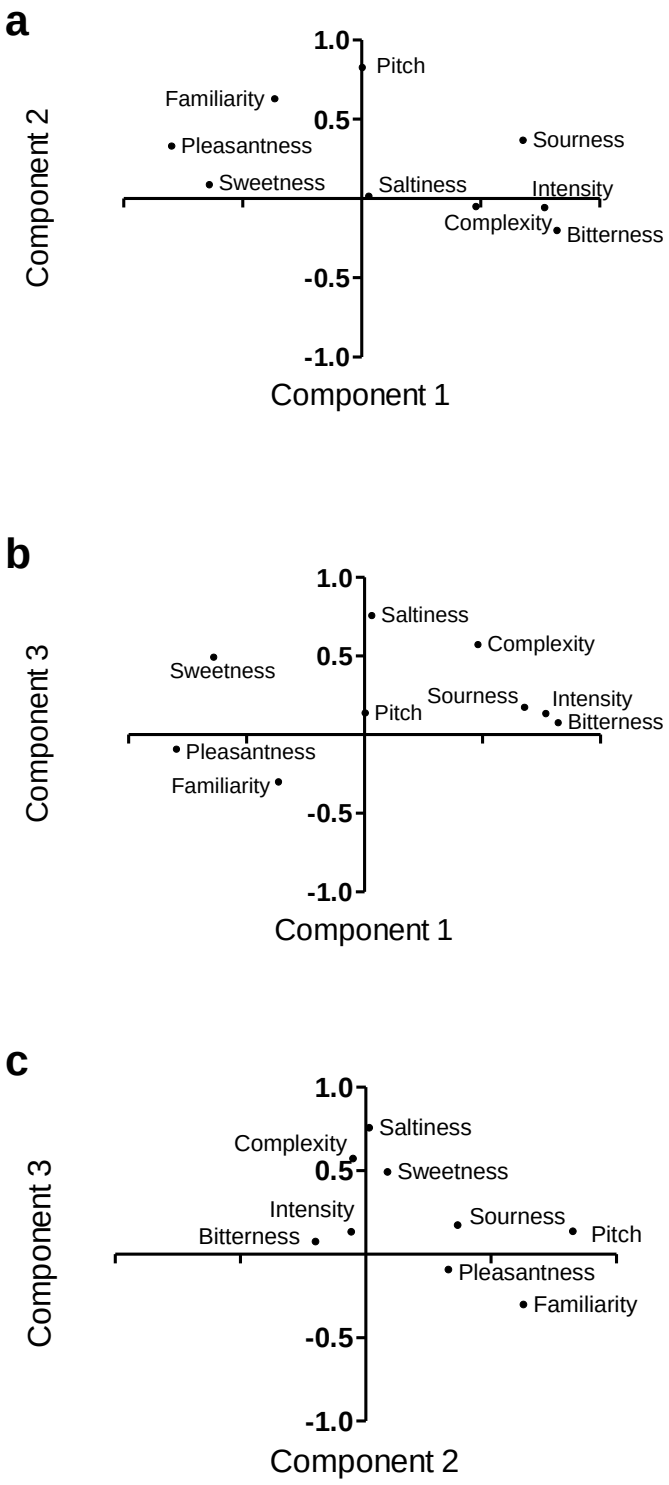


Figure 3.12: Two-dimensional projections of the loadings of the pitch and the various ratings on the rotated components extracted through PCA for the data collected in Experiment 3.2. First and second components (a), first and third components (b), and second and third components (c).

3.3.2.8 Control study

Participants in the control study were unable to detect the difference between milks of varying fat content (*M* = 49% correct, *SD* = 22%, chance level was 50%). Even the largest difference (whole vs. skimmed milk) was not detected by 5 out of 12 of the participants. It should be noted that samples were presented in opaque white cups, so that participants could not rely on visual cues to detect differences between the milks.

3.3.3 Discussion

The expected significant effect of flavour on the choice of pitch and instrument was observed. The crossmodal matching of flavours to pitches would thus appear to be a robust empirical phenomenon, one that still holds in the context of more complex and ecologically-valid food stimuli. Moreover, as pitch randomly increased from either left to right or right to left (which was not the case in Experiment 3.1), a role of associations between flavours and spatial position can be excluded. The chosen pitches for lemon and orange flower flavours (*M* = 65.0, *M* = 62.8) were comparable to those obtained for the same flavours presented in water (*M* = 66.3, *M* = 59.5; see Experiment 3.1). However, the difference between these two flavours did not reach statistical significance in the present study. This might have been due to the flavours contributed by the milk decreasing the perceived difference between the lemon and orange flower flavours. The unexpectedly low pitch chosen for the vanilla flavour (*M* = 54.7 vs. *M* = 61.0 in Experiment 3.1) might be explained by the use of vanilla flavouring in the present experiment (instead of vanilla extract, as in Experiment 3.1), leading to high bitterness ratings and consequently low pleasantness ratings.

The influence of flavours on the choices of instruments was partially replicated. Plain milk was preferentially associated with the piano, while other flavours did not lead to significant preferences. Pleasantness again seems to be an important factor in the choice of instrument, the piano being preferred for pleasant stimuli, while brass instruments were associated with

unpleasant stimuli. The stimuli matched to brass instruments were also judged to be more bitter and sour. This corresponds to a matching of the hedonic value in both sensory modalities.

Contrary to the flavour effect, the variation in fat content did not seem to influence either the choice of pitch or of instrument. This is consistent with the fact that, as shown by the results of the control experiment, participants were unable to differentiate between the different types of milk. This somewhat surprising result might have been caused by the method of presentation of the samples, namely in opaque white cups, thus limiting the visual inspection of the milk. Indeed, it has been reported previously that appearance is more important than texture in terms of identifying fat content in milk (Frøst, Dijksterhuis, & Martens, 2001). Differences in fat content did, however, not go completely undetected, as shown by their effect on pleasantness and intensity ratings given by the participants (see Figure 3.10, panels a and b). These results therefore suggest that while fattiness is detected physiologically, it might not constitute an essential component of our cognitive representation of taste. Depending on how basic tastes are defined, an issue that is widely debated (Delwiche, 1996; Erickson, 2008), it might thus not be appropriate to add fat to the list. It should, however, be noted that in the present experiment, as already mentioned, differences in the fat content of stimuli were small, which might be the reason for the absence of crossmodal associations with musical notes.

PCA conducted on the various ratings of the samples, as well as the pitch matched to the samples, suggests three components (see Figure 3.12). The first component seems to be linked to the hedonic evaluation of the stimuli. The interpretation of the second and third components is less clear. The second component has strong loadings of both pitch and familiarity, suggesting that familiarity might play a role in the choice of pitch. Finally, the third component, with strong loadings of saltiness and complexity, might reflect the perceived complexity of the stimulus. This analysis gives quite a different picture to the one obtained in Experiment 3.1 (only two components, linked respectively to hedonic value and intensity). Several factors might have

caused the differences between the two analyses. First, familiarity was added to the present analysis, and it seems to be correlated with the choice of pitch. Second, this experiment used a set of similar stimuli, using only four flavour conditions, all presented in milk. Thus, participants might have found it difficult to rate the stimuli on certain scales, for which there was not much variations between the stimuli. This might have particularly affected saltiness, which has the strongest loading on the third component, but did not actually vary between the samples, and might thus reflect the difficulty that participants had in describing the stimuli, a hypothesis strengthened by the fact that complexity also has a strong loading on that component.

3.4 Experiment 3.3

The goal of Experiment 3.3 was to examine crossmodal associations involving food products in a marketing context. Walkers recently modified the packaging of one of their ranges of crisps called Walkers' Sensations. The visual imagery used on the packaging of this product range appears to have been designed in order to convey a multisensory experience: The background colour for the packaging is black, with the word *Sensations* printed in white ink. There's a big *S* shape on the front of each package (see Figure 3.13). However, it is printed in a different colour for each of the seven different flavours in the range. The large *S* shape is filled with (or made up of) pictures of the ingredients corresponding to the flavour, but also other pictures and patterns. Interestingly, some flavours include pictures of musical instruments (see Table 3.5), which are not often represented on food packaging[3]. One important question that arises from the Sensations range of crisps is whether the instruments paired with the different flavours of the crisps, as well as the patterns and colours, match crossmodally. The challenge that was tackled in Experiment 3.3 was therefore to determine whether the methods developed

[3] Since the study was conducted, Walkers has once again modified the design of the packaging for its Sensations range. The 'S' shape has been replaced by a bigger picture representing the ingredients present in the flavour. Unrelated pictures have been removed, and the use of shapes and patterns is limited, and very similar for the various flavours.

in Experiment 3.1 and 3.2 could be used to assess the appropriateness of the stimuli/patterns/colours chosen for each of the seven flavours of crisp.

Table 3.5: Main features of the packaging design for the seven crisp flavours from the Walkers Sensations range used in Experiment 3.3.

Flavour	Main colour	Musical instruments
Southern style barbecue	White	Brass instruments
Vintage cheddar and onion chutney	Yellow	-
Roasted chicken and thyme	Green	Trumpet
Thai sweet chilli	Red	-
Balsamic vinegar and caramelised onion	Purple	String instrument
Oriental red curry	Orange	-
Roasted tomato and aromatic spices	Pink	Percussion instruments



Figure 3.13: Packaging of one of the crisp flavours used in Experiment 3.3: Southern style barbecue. Note the presence of the brass instruments in the upper half of the "S".

3.4.1 Methods

3.4.1.1 Participants

22 participants took part in Experiment 3.3 (14 females, aged 17-33 years), which was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their senses of taste and smell, and no hearing impairment. The experiment lasted for approximately 15 minutes.

3.4.1.2 Stimuli

Seven flavours of crisps were used in Experiment 3.3: balsamic vinegar and caramelised onion, oriental red curry, roasted chicken and thyme, roasted tomato and aromatic spices, southern style barbecue, Thai sweet chilli, and vintage cheddar and onion chutney (all manufactured by Walkers, UK). Samples consisted of one average-sized crisp.

The auditory stimuli were the same as in Experiment 3.1.

The colour stimuli consisted of 10 circles (6 cm in diameter) filled in black (RGB values: 0,0,0), blue (0,0,255), green (0,255,0), grey (221,221,221), orange (254,136,18), pink (255,102,255), red (255,0,0), purple (182,1,255), yellow (255,255,0), or white (255,255,255).

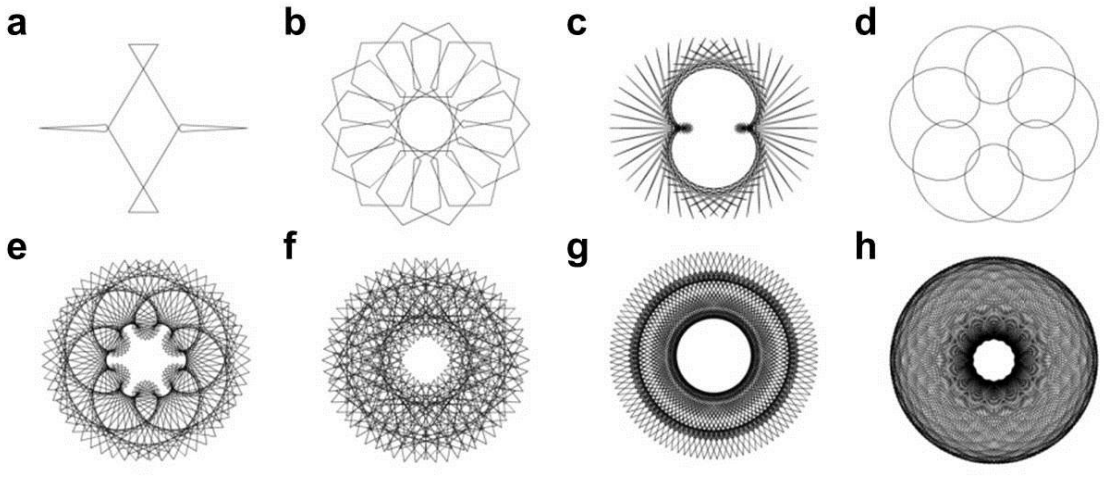


Figure 3.14: Guilloché patterns used in the flavour-shapes matching task in Experiment 3.3. The only variable was the number of steps: 10 (a), 70 (b), 130 (c), 190 (d), 291 (e), 310 (f), 490 (g), and 2730 (h).

The shape stimuli were created using an online Guilloché pattern generator (available at: http://www.subblue.com/projects/guilloche, downloaded on 14/06/2011). The following parameters were used: scale: 2.5, multiplier: 1, major ripple: 49, minor ripple: 0.25, radius: 33, opacity: 1, thickness: 1. The number of steps was the only parameter that varied. Eight patterns were used, with the following number of steps: 10, 70, 130, 190, 291, 310, 490, 2730 (see Figure 3.14).

3.4.1.3 Procedure

The experiment was programmed in E-Prime (version 1.2). The participants were first given the number of the sample that they were to taste. They were then given the crisp by the experimenter and instructed to follow the on-screen instructions. The sounds were presented as in Experiment 3.2. The participants were free to click on as many of the sounds as they wished before making their choice. Next, the participant chose one of ten colours to match to the flavour by checking a box under the colour of their choice. The participants then rated the flavour on a 9-point scale anchored by an angular shape and a rounded shape (see Figure 3.17 for the shapes used to anchor the scale). The participants were then presented with the 8 Guilloché patterns and instructed to pick the pattern that best matched the flavour of the crisp. Next, they rated the bitterness, saltiness, sourness, sweetness, intensity, complexity, and pleasantness of the sample using 9-point scales. These ratings were made in a random order. All of the scales were anchored by the words *not at all* on the left side, and *extremely so* on the right. Finally, the participants had to try and identify the flavour of the crisp. The seven flavours of crisps were presented once in a random order. The participants were instructed to rinse their mouth with tap water after tasting each sample. At the end of the experiment, participants were instructed to fill in a questionnaire with the following questions: “How often do you eat crisps?” (possible answers were: 1-2 times a year or less, several times a year but less than once a month, 1-3 times a month, once a week, or several times a week), “Which brand(s) do you have most often?”, “Have you ever tasted the Walkers Sensations range?”, “Have you ever seen

the design of the Walkers Sensations range packaging?", and "If yes, can you briefly describe it?"

3.4.1.4 Data Analysis

Repeated-measures ANOVAs were used for the interval data (choice of pitch, angular vs. rounded shape scale, and ratings), with flavours as a within-subjects variable. Fisher's exact tests were used for nominal data (choice of instrument, colour, and Guilloché patterns), as the expected frequencies were too low to use Pearson's chi-square test.

3.4.2 Results

3.4.2.1 Knowledge of crisps

Eleven of the participants cited Walkers as (one of) the brands that they consumed most frequently, and stated that they had tasted the Sensations range before. Fourteen of the participants had seen the packaging of the Sensations range of crisps and were able to describe it briefly. However, each participant was able to identify at most three of the flavours correctly (M = 0.77). It is thus unlikely that their choices and ratings were influenced by their knowledge of the flavours and the corresponding design on the packaging.

3.4.2.2 Pitch

A repeated-measures ANOVA was conducted in order to assess whether there were any differences between the average pitch matched to the seven flavours of crisps. The results indicated that the participants matched the seven flavours to pitch differently, $F(6, 126) = 3.32$, $p = .005$ (see Figure 3.15).

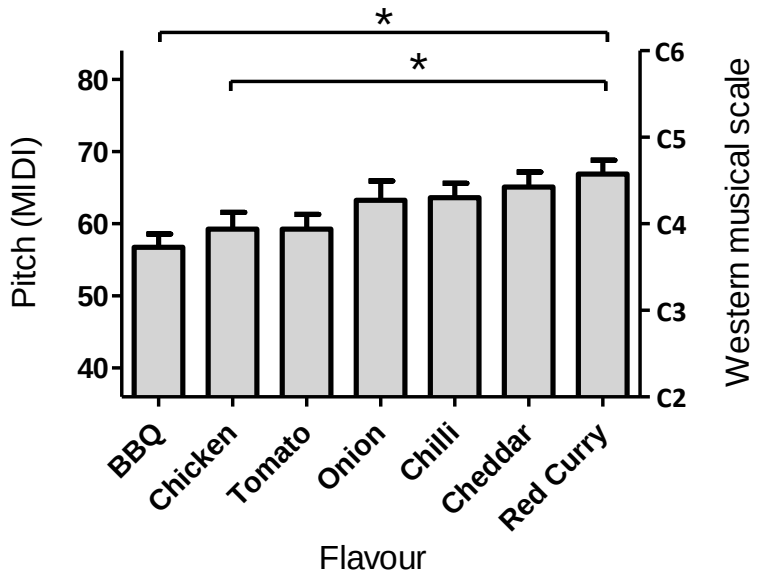


Figure 3.15: Mean pitch matched to each crisp flavour in Experiment 3.3: Southern style barbecue (BBQ), roasted chicken and thyme (chicken), roasted tomato and aromatic spices (tomato), balsamic vinegar and caramelised onion (onion), Thai sweet chilli (chilli), vintage cheddar and onion chutney (cheddar), and oriental red curry (red curry). MIDI note numbers were used to code the pitch of the chosen notes. Western musical scale notation is shown on the right-hand y-axis. Error bars represent the SEM. Significant differences (post-hoc, Bonferroni-corrected *t* tests, $p < .05$) are marked by an asterisk.

3.4.2.3 Types of instruments

Fisher's exact tests were used in order to assess whether flavours elicited a choice of instrument different from that expected by chance. The results indicated that none of the flavours influenced the choice of instruments (all $p > .1$).

3.4.2.4 Colours

Fisher's exact tests were used in order to assess whether flavours elicited a choice of colour different from that expected by chance. The results indicated that all flavours led to preferences in the choice of colour ($p < .05$), with the exception of caramelised onion and balsamic vinegar ($p = .089$). However, the actual colour of the crisps seems to have been an important factor in determining participants' choices, as the preferred colours overall were yellow, orange, and red (see Figure 3.16). Yellow was preferred for the vintage cheddar and onion chutney, as well as roasted chicken and thyme flavours. Orange was preferred for the southern style barbecue, as well as for the roasted tomato and aromatic spices flavours. Red

and orange were preferred for the Thai sweet chilli flavour. Finally, green was preferred for the oriental red curry flavour. It would thus seem that the participants' preferred colour did not match the dominant colour used on the packaging in the majority of cases, with the exception of vintage cheddar and onion chutney and, to some extent, roasted chicken and thyme, and Thai sweet chilli.

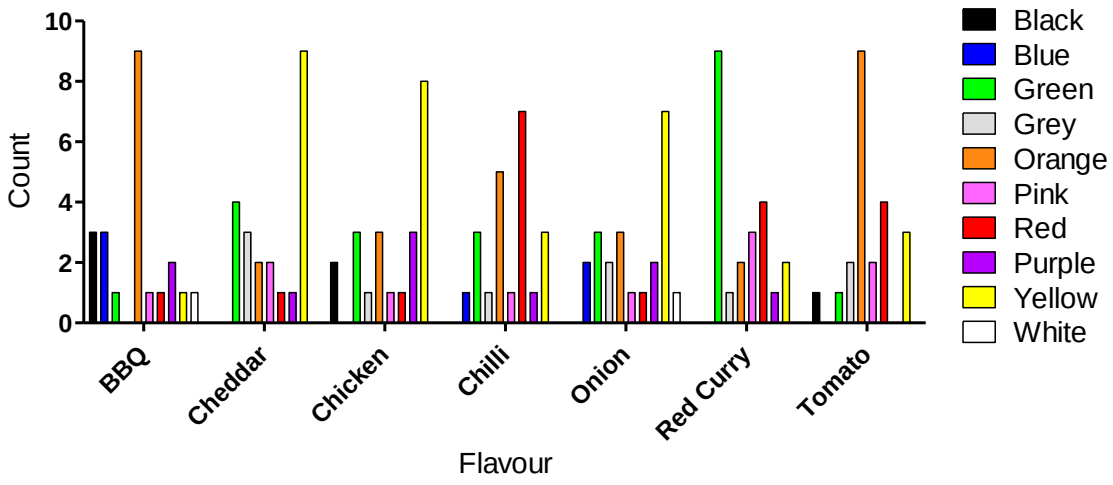


Figure 3.16: Choice of colour as a function of the flavour tasted in Experiment 3.3. The total count per category is 22.

3.4.2.5 Shapes and patterns

A repeated-measures ANOVA was conducted in order to assess whether there were any differences between the ratings on the angular versus rounded shape scale for the seven flavours. In this case, the variations in participants' ratings did not reach statistical significance, $F(6, 126) = 1.77$, $p = .110$ (see Figure 3.17). Instead, all responses fell close to the mid-point of the scale, in contrast to the results obtained with a variety of other food items (e.g., chocolate, Ngo et al., 2011; still and sparkling water, Spence & Gallace, 2011). Fisher's exact tests were used to assess whether flavours elicited a choice of Guilloché pattern different from that expected by chance. The flavours did not significantly influence the choice of pattern, all $p > .05$. This contrasts with recent results demonstrating associations between shapes and flavours (of beers, Deroy & Valentin, 2011), and shapes and odours (Seo et al., 2010).

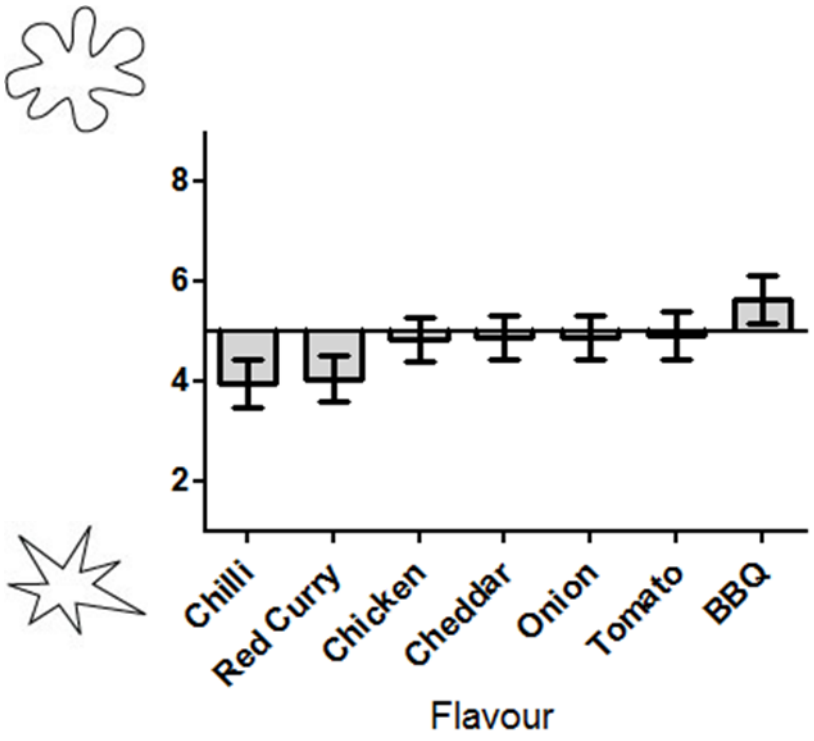


Figure 3.17: Mean ratings on the shape scale (anchored with an angular and rounded shape) for each of the seven flavours: Southern style barbecue (BBQ), roasted chicken and thyme (chicken), roasted tomato and aromatic spices (tomato), balsamic vinegar and caramelised onion (onion), Thai sweet chilli (chilli), vintage cheddar and onion chutney (cheddar), and oriental red curry (red curry) tested in Experiment 3.3. Error bars represent the SEM.

3.4.2.6 Ratings

A repeated-measures ANOVA was conducted in order to assess whether the seven flavours were rated differently in terms of their bitterness, saltiness, sourness, sweetness, complexity, intensity, and/or pleasantness. The results indicated that only the intensities of the seven flavours of crisps were rated differently by participants, $F(6, 126) = 3.99$, $p = .001$. However, that said, many of the ratings were correlated to either or both the choice of pitch and the rating of the angular vs. rounded shape (see Table 3.6).

Table 3.6: Pearson correlations between the choice of pitch and ratings in Experiment 3.3. Significant values ($p < .05$) are highlighted in bold font.

	Shape	Pitch	Complex	Intense	Pleasant	Bitter	Salty	Sour	Sweet
Shape		**-.257**	-.144	**-.279**	.106	**-.212**	-.124	-.137	**.233**
Pitch	**-.257**		.000	.064	**.165**	**-.191**	.006	.063	.032
Complex	-.144	.000		**.412**	**.201**	**.242**	**.526**	**.396**	**.250**
Intense	**-.279**	.064	**.412**		.109	**.411**	**.459**	**.322**	**.201**
Pleasant	.106	**.165**	**.201**	.109		**-.232**	**.271**	-.088	**.423**
Bitter	**-.212**	**-.191**	**.242**	**.411**	**-.232**		**.274**	**.614**	.002
Salty	-.124	.006	**.526**	**.459**	**.271**	**.274**		**.319**	.074
Sour	-.137	.063	**.396**	**.322**	-.088	**.614**	**.319**		.050
Sweet	**.233**	.032	**.250**	**.201**	**.423**	.002	.074	.050	

3.4.3 Discussion

The crisps used in Experiment 3.3 were very similar in terms of their appearance and texture. They were also rated by participants as being similar in terms of their complexity, pleasantness, bitterness, saltiness, sourness, and sweetness. The only rating that varied significantly as a function of the crisp variety was the intensity of the overall flavour. Despite this high degree of similarity, differences in the pitch and colour chosen to match the different flavours were found. It would appear as though the flavours themselves drove these associations. Higher pitch was correlated with more pleasant, and less bitter stimuli, as well as with stimuli that were associated with the angular shape.

The participants in Experiment 3.3 did not appear to make consistent crossmodal associations between the flavours and instrument types. This might be due to the fact that the flavours of the crisps did not differ significantly in terms of their pleasantness, as the choice of instrument has been shown to be influenced by the pleasantness of food stimuli (Experiment

3.1 and 3.2, see also Experiment 4.1). It might thus not seem to have been relevant to include musical instruments in the design of the packaging of some of the flavours, at least not if the choice of instrument was meant to convey some information about the likely sensory-discriminative or hedonic properties of the packaging's contents.

Specific colours were consistently matched to specific flavours. However, this effect seems to have been driven mainly by the colour of the crisps themselves, as the preferred colours overall were yellow and orange (see Figure 3.16). It is interesting to note that neither red oriental curry, nor roasted tomato and aromatic spices were associated with the colour red (but were associated instead with green and orange, respectively), suggesting that in these cases, the choice of colour was not based on the actual colour of the ingredients making up the flavour (cf. Demattè, Sanabria, et al., 2006). The colours that were chosen least frequently were white, black, blue, and grey (though note that strictly-speaking, black, white, and grey are not colours). It would thus seem that in order to induce the correct expectations in the minds of consumers, packaging designs should probably use the colours of the food item itself, and avoid colours that are rarely found in natural food products.

The associations between certain flavours and certain shapes, found previously for other food items (sparkling and still water, Spence & Gallace, 2011; chocolate varying in its cocoa content, Ngo et al., 2011; beers, Deroy & Valentin, 2011), were not found for the food items used in Experiment 3.3. One suggestion is that these crossmodal associations (or correspondences) might thus be mostly based on the oral-somatosensory texture (see also Ngo & Spence, 2011), a factor that varied minimally in Experiment 3.3. Alternatively, it might be based on presence/strength of basic tastes (see Dichter, 1971; Spence, Percival, Smith, & Ngo, submitted) which, once again, did not differ much in this study. It might thus be necessary to use a wider range of food stimuli in order to observe strong crossmodal shape associations. Dichter, for example, suggested that people match sweetness with roundness and angularity

(specifically a triangular shape) with bitterness. Similarly, it was the variation in bitterness that correlated with the angularity of the shape chosen by participants in Ngo et al.'s recent study of chocolate that varied in its cocoa content. It would therefore be interesting in future research to explore more complex shapes, such as the patterns used in the present study, in relation to food items varying in both their oral-somatosensory texture and their basic tastes properties (cf. Deroy & Valentin, 2011; Seo et al., 2010).

3.5 Experiment 3.4

3.5.1 Methods

3.5.1.1 Participants

30 participants took part in Experiment 3.4 (22 females, aged 18-55 years). The experiment was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their senses of smell, and no hearing impairment. The experiment lasted for approximately 40 minutes and the participants were compensated for their time with a £5 (UK Sterling) gift voucher.

3.5.1.2 Stimuli

Samples from the Nez du Vin aroma kit (Brizard & Co, Dorchester, UK) were used as olfactory stimuli. The kit is designed to help wine amateurs learn the odours commonly found in wine. Odours are represented either by a single typical molecule or a mix. Twenty out of the 54 samples from the kit were selected (almond, apple, apricot, blackberry, caramel, cedar, dark chocolate, cut hay, green pepper, honey, lemon, liquorice, mushroom, musk, pepper, pineapple, raspberry, smoked, vanilla, and violet). The selection aimed to cover a wide range of odours. The samples were presented in small glass bottles identified by a number written on the side of the bottle. The odours were used in the concentration provided in the kit.

The auditory stimuli were the same as in Experiment 3.1.

3.5.1.3 Procedure

The experiment was programmed in E-Prime (version 1.2). The participants were first given the number of the sample that they were to smell. After opening the glass bottle and smelling its content orthonasally, they had to choose a sound to match the smell. The sounds were presented as in Experiment 3.2. After having made their response, they rated the appropriateness of a range of adjectives to describe the smell on 9-point scales. The adjectives rated included three categories: amodal descriptors (complex, familiar, intense, and pleasant), odour descriptors (acrid, earthy, floral, fruity, nutty, spicy, and woody), and taste descriptors (bitter, salty, sour, and sweet). This last category was added in order to compare the results of Experiment 3.3 with the results of the previous experiments. Odours are known to be commonly described by taste adjectives (Stevenson, Prescott, & Boakes, 1995). All the scales were presented one at a time in a random order, and were anchored by the words *not at all* on the left side, and *extremely so* on the right side. Finally, the participants had to try and identify the sample and note down their response on a sheet listing all sample numbers. The 20 olfactory stimuli were presented once in a random order. The participants were free to smell the sample as often as they liked during a trial.

Although the participants were instructed to focus on the odour of the stimuli, their colour (which ranged from dark brown to transparent) might have affected the chosen pitch, as lower pitched sounds tend to be associated with darker colours (Melara, 1989). Thus, as a control for the influence of the colour of the samples, the last eight participants were blindfolded while smelling the samples, which were handed to them by the experimenter.

3.5.1.4 Data Analysis

Missing answers were replaced by the mean of the variable, as there was no more than one missing data point by variable, and no participant fail to respond on more than two occasions. Mixed ANOVAs were used for interval data (choice of pitch and ratings), with odours

as a within-subjects variable and being blindfolded as a between-subjects variable. The data were further subjected to a PCA.

For nominal data (choice of instrument), chi-square tests were used. In order to evaluate the correlations between ratings and the choice of instrument, the means of the ratings for each instrument were computed for each participant. These values were then analysed with repeated-measures ANOVAs (Greenhouse-Geisser corrected).

3.5.2 Results

3.5.2.1 Pitch

A mixed ANOVA, with Greenhouse-Geisser correction, was conducted in order to assess whether the odours or visual information affected the participants' choice of pitch. The results indicated that the odours affected the choice of pitch, $F(9.94, 278.19) = 11.33$, $p < .001$ (see Figure 3.18). Visual information had no main effect on the choice of pitch, $F(1, 28) = .259$, $p = .615$, and the interaction between visual information and odour was not significant, $F(9.94, 278.19) = .94$, $p = .50$. The range of chosen pitches (54.6-72.3, in MIDI note numbers) was very similar to the range found for tastes/flavours in Experiment 3.1 (50.8-71.5).

3.5.2.2 Types of instruments

Chi-square tests for goodness of fit were conducted to determine which odours induced a distribution of instrument choice that was different from that expected by chance. Out of the 20 odours used, 5 gave rise to significant preferences in the choice of instrument: apricot ($\chi^2(3, N = 30) = 14.53$, $p = .002$), blackberry ($\chi^2(3, N = 30) = 18.53$, $p < .001$), musk ($\chi^2(3, N = 30) = 8.13$, $p = .04$), raspberry ($\chi^2(3, N = 30) = 13.47$, $p = .004$), and vanilla ($\chi^2(3, N = 30) = 11.07$, $p = .01$) (see Figure 3.19).

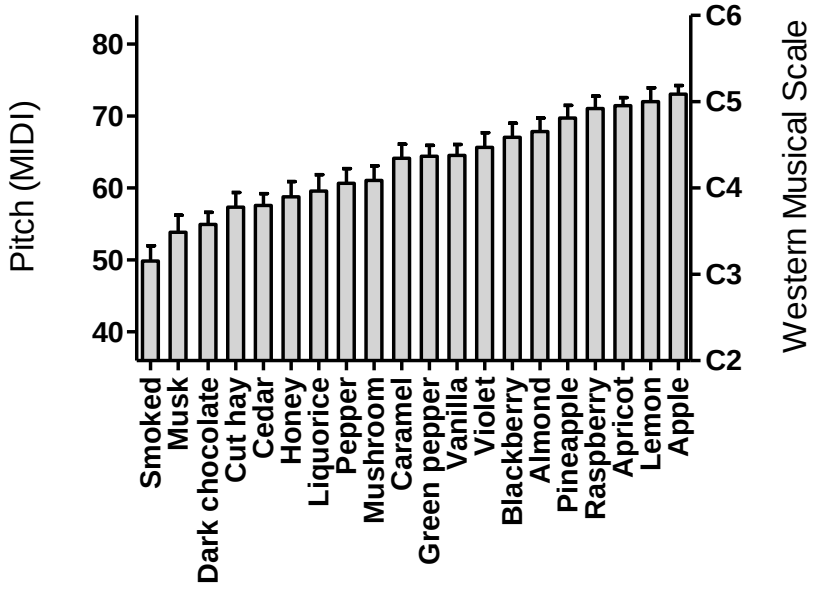


Figure 3.18: Mean pitch matched to each odour. MIDI note numbers were used to code the pitch of the chosen notes in Experiment 3.4. Western musical scale notation is shown on the right-hand y-axis. Error bars represent the SEM. High-pitched notes were preferred for fruits.

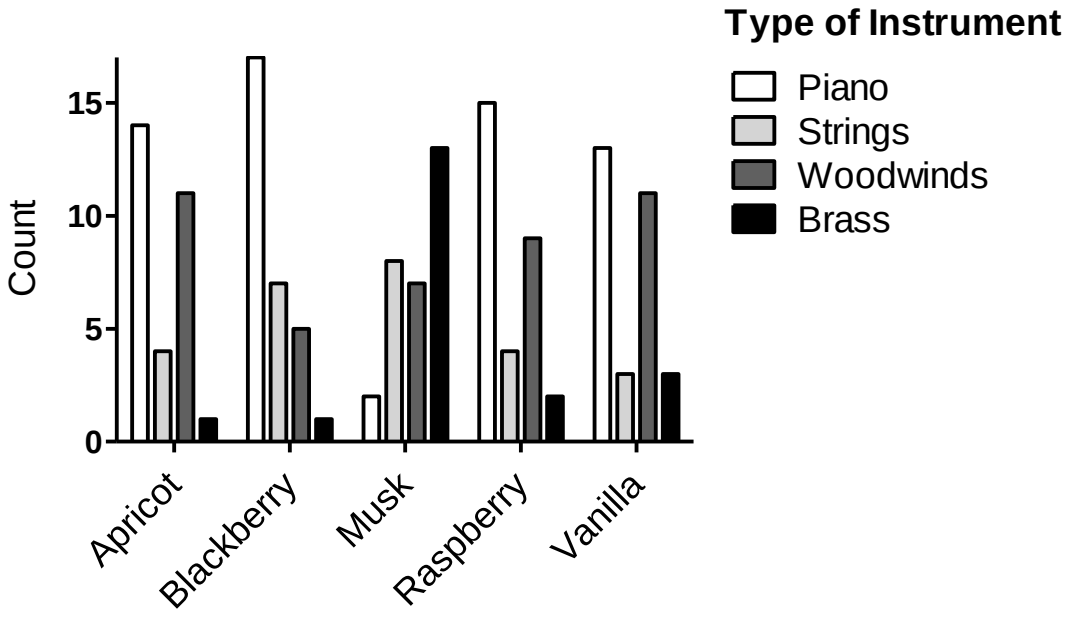


Figure 3.19: Choice of instrument as a function of the odour presented in Experiment 3.4. Only odours that led to significant preferences for instruments are shown. The total count per category is 30.

Repeated-measures ANOVAs were used to determine whether odours associated with different instruments were rated differently by participants. The choice of instrument led to

different ratings for complex, intense, familiar, pleasant, acrid, floral, fruity, bitter, salty, sour, and sweet (see Table 3.7, Figure 3.20, 3.22, and 3.23).

Table 3.7: Descriptive ratings of odours (amodal, olfactory, and gustatory descriptors) for different choices of instruments assessed by repeated-measures ANOVAs in Experiment 3.4. Significant results ($p < .05$) are in bold.

	Instruments					
	piano	**strings**	**woodwinds**	**brass**	**F**	***p***
Complex	**4.97**	**5.59**	**5.13**	**5.74**	**3.32**	**.036**
Familiar	**6.55**	**5.88**	**6.13**	**5.52**	**3.18**	**.038**
Intense	**5.39**	**5.61**	**5.78**	**6.69**	**9.34**	**< .001**
Pleasant	**6.54**	**5.22**	**5.13**	**3.59**	**21.86**	**< .001**
Acrid	**2.33**	**3.29**	**3.51**	**4.83**	**17.19**	**< .001**
Earthy	3.71	4.19	3.75	3.72	1.03	.37
Floral	**5.04**	**4.19**	**4.08**	**2.87**	**17.45**	**< .001**
Fruity	**5.69**	**4.24**	**4.65**	**3.43**	**12.45**	**< .001**
Nutty	2.93	3.06	3.01	2.96	0.11	.94
Spicy	2.92	3.48	3.15	4.19	1.73	.18
Woody	3.51	3.91	3.88	3.71	0.74	.52
Bitter	**2.72**	**4.11**	**3.84**	**5.02**	**15.18**	**< .001**
Salty	**2.17**	**2.73**	**2.39**	**3.38**	**6.38**	**.005**
Sour	**2.61**	**3.35**	**3.57**	**4.19**	**6.14**	**.004**
Sweet	**5.92**	**4.59**	**5.16**	**3.62**	**14.38**	**< .001**

3.5.2.3 Ratings of odours

Mixed ANOVAs (Greenhouse-Geisser corrected) were conducted to check whether the participants rated the odours differently on the descriptive scales (complex, familiar, intense, pleasant, acrid, earthy, floral, fruity, nutty, spicy, woody, bitter, salty, sour, and sweet) and if the visual appearance of the sample had an effect on the ratings. The results demonstrated a

significant main effect of the odour on the ratings of all adjectives ($p < .05$), but not of being blindfolded. The interaction between odour and being blindfolded was not significant, except for the ratings of woodiness ($F(9.13, 255.50) = 2.18$, $p = .02$) and sweetness ($F(9.79, 274.09) = 2.01$, $p = .03$).

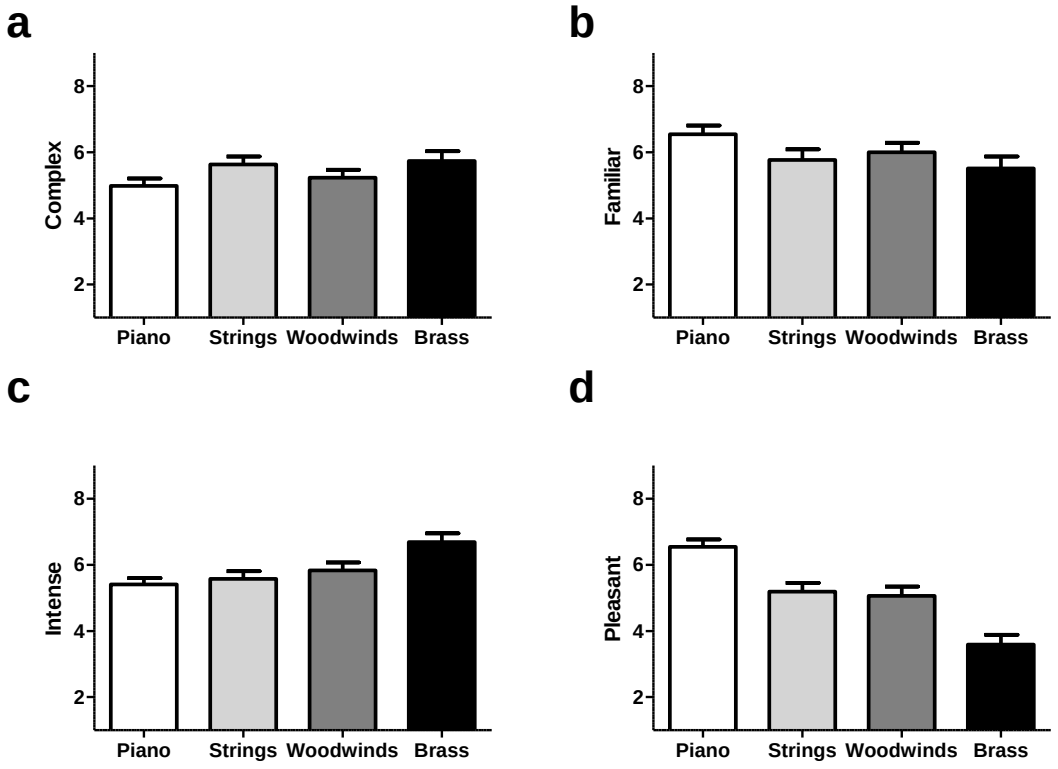


Figure 3.20: Ratings of amodal descriptors as a function of the choice of instrument in Experiment 3.4: complex (a), familiar (b), intense (c), and pleasant (d).

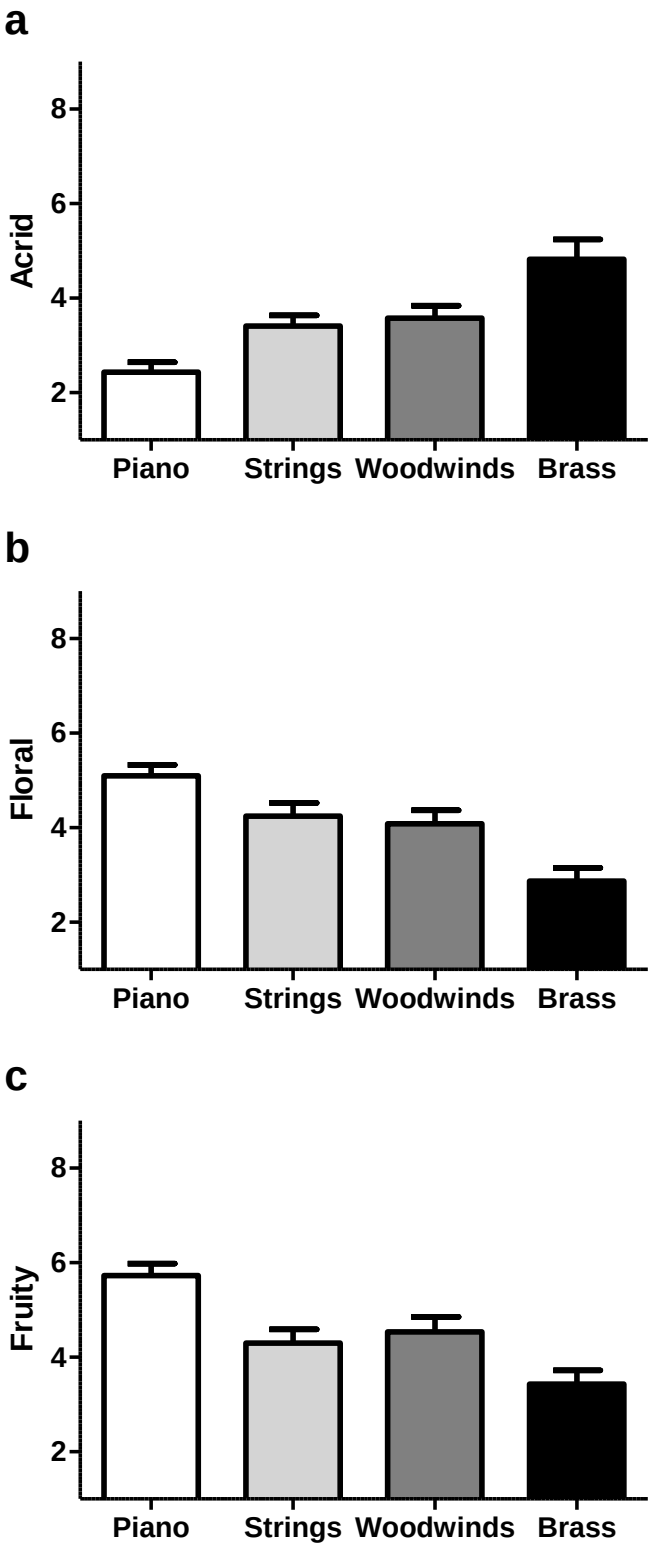


Figure 3.21: Ratings of olfactory descriptors as a function of the choice of instrument in Experiment 3.4 (only adjectives significantly affected by the choice of instrument are shown): acrid (a), floral (b), and fruity (c).

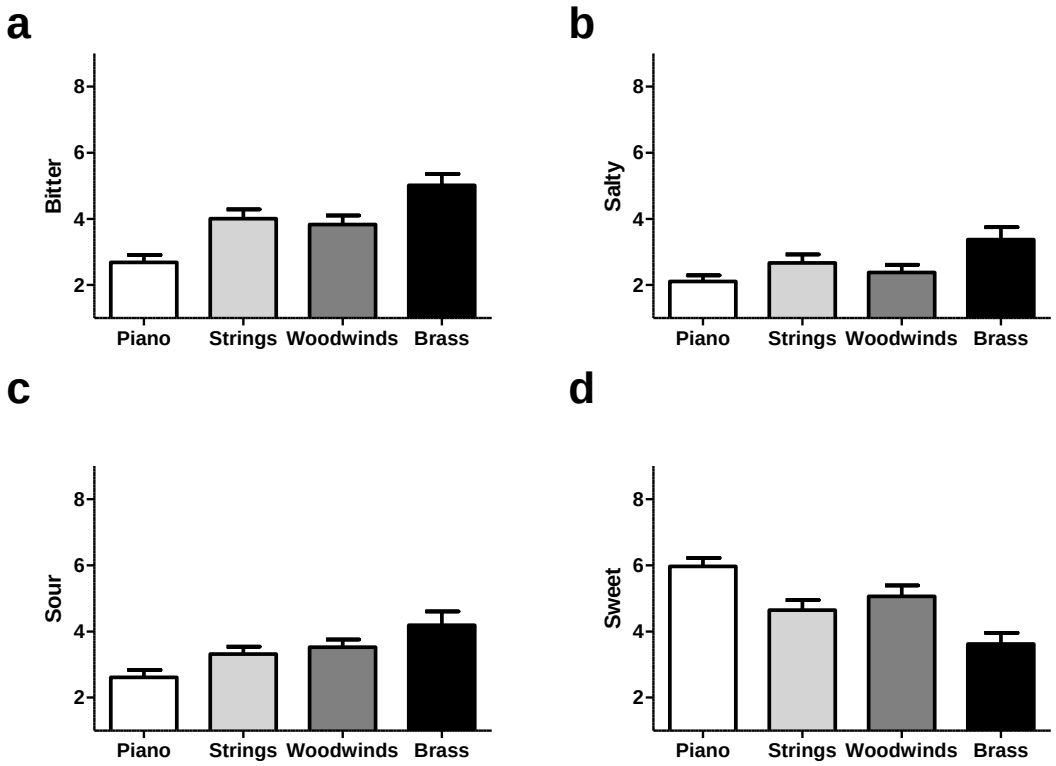


Figure 3.22: Ratings of taste descriptors as a function of the choice of instrument in Experiment 3.4: bitter (a), salty (b), sour (c), and sweet (d).

3.5.2.4 Identification

Participants' responses in terms of identifying the odours were classified into three categories: exact identification, identification of the sample category (for example, naming another citrus fruit for lemon, or another berry for raspberry), and incorrect identification. The participants correctly (and exactly) identified the olfactory stimulus in 17.7% of cases. In a further 17.3% of cases, they identified the category of the stimulus correctly. These figures varied greatly depending on the odour under consideration: No participant was able to identify the blackberry or the violet (10% identified that it was a kind of berry, respectively of flower), while 53.3% identified the lemon odour correctly, with a further 30% recognizing it as a citrus fruit.

One-way ANOVAs revealed that the identification of the stimulus had an influence on the ratings of familiarity ($F(2, 597) = 45.04$, $p < .001$), intensity ($F(2, 597) = 7.91$, $p < .001$),

pleasantness ($F(2, 597) = 28.07$, $p < .001$), acridity ($F(2, 597) = 8.29$, $p < .001$), fruitiness ($F(2, 597) = 5.98$, $p = .003$), nuttiness ($F(2, 597) = 7.58$, $p = .001$), spiciness ($F(2, 597) = 4.20$, $p = .015$), saltiness ($F(2, 597) = 8.10$, $p < .001$), and sweetness ($F(2, 597) = 6.66$, $p = .001$). Correctly identified stimuli were rated as less acrid, nutty, and salty, and more familiar, intense, pleasant, fruity, spicy, and sweet.

3.5.2.5 Principal components analysis

The pitch, as well as the 15 other ratings (complex, familiar, intense, pleasant, acrid, earthy, floral, fruity, nutty, spicy, woody, bitter, salty, sour, sweet), were subjected to PCA. The suitability of this approach was assessed first. The correlation matrix revealed the presence of several coefficients above .3. The Kaiser-Meyer-Oklin value was .82, thus attaining the recommended value of .6 (Kaiser 1970, 1974), and the Bartlett's test of sphericity (Bartlett 1954) reached statistical significance, supporting the factorability of the correlation matrix. PCA revealed the presence of four components with eigenvalues over 1, explaining 29.6%, 15.2%, 10.5%, and 6.7% of the variance, respectively. We decided to keep only three components, based on the inspection of the scree plot and results of parallel analysis (using the program Monte Carlo PCA for Parallel Analysis, developed by Marley Watkins, 2000), which demonstrated three components with eigenvalues exceeding the corresponding criterion values for a randomly generated data matrix of the same size (16 variables by 600 trials). Varimax rotation was performed. The first component contributed 20.8% of the total variance explained (55.3%), while the second and third components contributed 20.3% and 14.2%, respectively (see Figure 3.23).

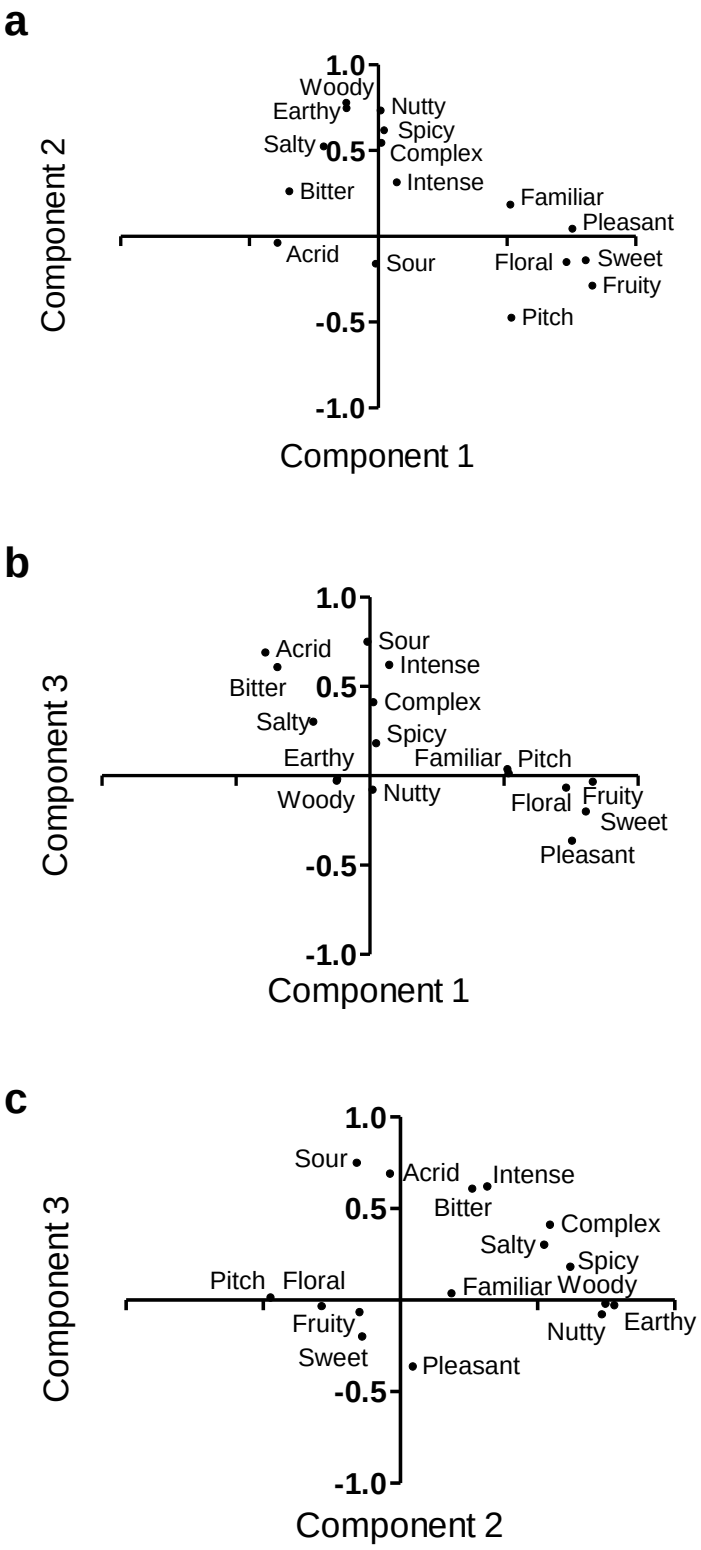


Figure 3.23: Two-dimensional projections of the loadings of the pitch and the various ratings on the rotated components extracted through PCA in Experiment 3.4. First and second components (a), first and third components (b), and second and third components (c). The first component is linked to hedonic value, the second component to complexity, and the third component to intensity.

The first component had strong positive loadings of familiar (.513), pleasant (.754), floral (.732), fruity (.832), and sweet (.806), while acrid (-.391) and bitter (-.345) had strong negative loadings on it. This suggests that the first component represents the hedonic evaluation of the olfactory stimuli. The second component had strong positive loadings of complex (.545), intense (.316), earthy (.747), nutty (.734), spicy (.619), woody (.780), and salty (.524), which suggests a connection with complexity (and maybe with the light-heavy dimension, see Zarzo & Stanton, 2009). Finally, the third component had strong loadings of complex (.413), intense (.621), salty (.303), and sour (.750), seemingly linking it to intensity. Pitch had a positive loading on the first component, and a negative loading on the second component. It thus seems that pleasantness and complexity were the essential factors in the choice of pitch.

3.5.3 Discussion

The results of Experiment 3.4 confirm the existence of consistent crossmodal associations between odours and pitch. Moreover, they also demonstrate that certain odours are preferentially matched to a specific type of musical instrument. The use of the term *note* to describe components of a perfume might thus be more than merely a metaphor.

Fruit odours seem to be consistently associated with high-pitched notes. This result accords well with previous results demonstrating that sour and sweet tastes, two qualities present in fruits, are associated with high pitch (Experiment 3.1). Given that taste qualities are easily associated with odours (see, for example, Stevenson et al., 1995), the extension of taste-sound associations to odours was to be expected. The similarity of the associations described here with those of tastes/flavours-notes associations from Experiment 3.1 seems to suggest that smelling the odours orthonasally as compared to retronasally does not necessarily affect the associations that people make. However, it should be noted that only 3 odours were present in both experiments (almond, lemon, and vanilla), and they weren't represented by the same chemical composition. Moreover, the flavours of Experiment 3.1 were presented in

solutions, adding taste and somatosensory sensations to the retronasal odours, thus preventing a rigorous comparison.

Unsurprisingly, participants were better able to name the odours that they rated as more familiar. Correctly identified stimuli were rated as more intense, possibly because more intense stimuli were easier to identify. The effect of identification on nuttiness is probably due to the fact that the almond odour, which was the only nut odour, was correctly (or nearly-correctly) identified in 54.4% of cases. Correctly identified stimuli were also rated as more pleasant. This result accords well with previous reports concerning the existence of a correlation between pleasantness and familiarity ratings of odours (see, for example, Distel et al., 1999). However, this correlation tends to vary with the odours under consideration and might have been reversed had more unpleasant odours been used (see, for example, Delplanque et al., 2008; Seo et al., 2008).

PCA suggests three components (see Figure 3.23). The first component is strongly linked to the hedonic evaluation of the olfactory stimuli. Many studies have shown that the hedonic value is a salient (or even the only, see Yeshurun & Sobel, 2010) psychological dimension of odours (Berglund, Berglund, Engen, & Ekman, 1973; Schiffman, Robinson, Louis, & Erickson, 1977; Zarzo, 2008; see also Section 1.2.7), thus confirming the validity of our approach on this data set. According to the PCA, the choice of pitch is linked to the first two components, i.e., hedonic value and complexity. Subjective intensity was not linked to the choice of pitch. However, it would probably have been matched between the olfactory and auditory stimuli if participants had been free to choose the intensity of the sound on top of the pitch and musical instrument.

Given that the perceived familiarity and pleasantness of olfactory stimuli are not independent (Delplanque et al., 2008; Distel et al., 1999), a higher familiarity with the odours would likely affect participants' pleasantness ratings. A version of this experiment was thus

repeated in wine specialists, for whom the familiarity of the odours is expected to be much higher (given that all of the stimuli were taken from an educational kit designed to learn the aromas found in wine; see Experiment 4.1).

Another extension of the experiment reported here would involve the use of different wines as stimuli, in order to have more complex and naturalistic stimuli. The differences between the stimuli would be smaller, and might only be easily detected by wine specialists. They might thus not be large enough to induce crossmodal associations with sounds. Additionally, though, there might be an added complication in that the nose of the wine (orthonasal smell) and its palate (involving the combination of taste and retronasal smell) might lead to different results. That said, it is clear that many wine writers already suggest that certain wines match (or are in some sense similar to) certain musical notes or pieces of music (see Spence, 2011, for a review).

3.6 General Discussion

The results of the experiments reported in Chapter 3 both confirm and expand the results of Chapter 2 in several ways. The associations between tastes and musical notes:

- are still present when using gustatory stimuli instead of merely the names of food items;
- can be explicitly expressed; and
- exist with both the pitch and the musical instrument playing the note.

Moreover, they have been demonstrated to occur for a range of chemosensory stimuli:

- basic tastes and flavours (Experiment 3.1),
- complex mixtures (milk-based solutions, Experiment 3.2),
- food items with similar features (crisps, Experiment 3.3), and
- orthonasally-smelled odours (Experiment 3.4).

The use of tastants and odorants excludes the possibility that the associations described in Chapter 2 may have been based solely on linguistic features of the names of the food items used. Moreover, perceptual features seem to be sufficient to elicit such crossmodal associations, as most participants performed poorly when trying to identify the stimuli, and thus had no access to their linguistic representation. The crossmodal associations demonstrated in Chapter 2 are thus confirmed: Both sweetness and sourness are associated with high pitch. Moreover, the association between bitterness and low pitch, which was supported by conflicting evidence in Chapter 2, was confirmed by the results of Experiment 3.1, where the participants associated the bitter stimulus (caffeine) with the lowest pitch.

The crossmodal associations highlighted in the experiments reported in this chapter between chemosensory stimuli and types of musical instruments demonstrate that these associations are not limited to pitch, but also occur with other auditory features, in this case timbre. This suggests the possibility that these crossmodal associations could extend to other auditory features and even to pieces of music. Music has been shown to activate brain mechanisms related to semantic processing and musical excerpts can prime related words (Koelsch et al., 2004). Both concrete (e.g., river, staircase) and abstract words (e.g., illusion, devotion) could be primed by short musical excerpts. It might thus also be possible to prime taste words. Indeed, in a recent study, Mesz et al. (2011) asked musicians to improvise short pieces of music in accordance to taste words (bitter, salty, sour, and sweet). The words elicited consistent and reliable musical patterns. Moreover, non-musical experts were found to be able to recognize the target word when listening to the improvisations.

The results of the experiments reported in this chapter therefore confirm the close links that exist between olfaction and gustation. The participants tested in the experiments reported here were able to use taste descriptors to describe odours in Experiment 3.3 (see Stevenson et al., 1995). Moreover, the associations were similar in both sensory modalities. For example, the

sour taste of citric acid, lemon flavour, and lemon odour were all associated with high-pitched notes.

PCAs gave somewhat contradictory results (see Table 3.8). However, pleasantness seems to be a constant, and to be reliably linked to the choice of pitch. This factor is thus studied in more details in Experiment 4.2. The intensity of the chemosensory stimuli was never linked to the choice of pitch. It is highly likely that intensity in both modalities would have been matched, had the participants been allowed to choose the intensity of the sound.

Table 3.8: Results of PCAs in Chapter 3, with suggested interpretation of the components. Components that have strong loadings of pitch are in bold.

	Stimuli	Component 1	Component 2	Component 3
Experiment 3.1	Taste and flavour solutions	**Pleasantness**	Intensity	-
Experiment 3.2	Milk-based flavour solutions	**Pleasantness**	**Familiarity**	Complexity
Experiment 3.4	Odours	**Pleasantness**	**Complexity**	Intensity

For the choice of instrument, the picture is somewhat clearer, with a consistent matching of hedonic value: For pleasant chemosensory stimuli, the piano, which was rated as the most pleasant instrument, is preferred; conversely, brass instruments are associated with unpleasant chemosensory stimuli.

The results of the experiments reported in this chapter demonstrate that, while some factors, such as pleasantness, familiarity, or complexity, have an impact on the matching of pitch to tastes at least in some cases (see Table 3.8), none of them is sufficient to completely explain the crossmodal associations that were observed. The fact that these three factors are subjective evaluations of the stimuli, rather than linked to any physical or chemical property of the stimuli, might be taken to indicate the importance of this type of evaluations in

chemosensory perception. Whereas for visual or auditory stimuli, identification might be the most important goal, for food items, it might be more important to evaluate whether an item is safe to ingest and whether it will have a pleasant taste.

Whatever the mechanism underlying these chemosensory-auditory associations is, they add to the growing list of crossmodal associations, which raises another question: Why do we associate stimuli from different sensory modalities so easily? One hypothesis that has been put forward is that we need to simplify the constant flow of sensory information to make sense of the complex world around us. To that end, it is useful to associate attributes from different sensory modalities, such as the colour of a fruit to its taste as it indicates its ripeness (Spence, Levitan, et al., 2010), as well as a deep, low-pitched growl to a large animal and a high-pitched squeak to a small one (a strategy that seemed to be used by dogs, see Faragó et al., 2010). This use of the correlations found in nature has been fruitfully modelled in terms of Bayesian theory (Ernst, 2006; Flanagan, Bittner, & Johansson, 2008; Spence, 2011b; see Section 1.1.1 for more detailed description and discussion). We might thus have evolved to easily compare and combine information from different sensory modalities, as a way to make better predictions when we only have partial information (see Bar, 2007). As a side-effect, we would tend to associate attributes even when they have no predictive value. Seeing synaesthesia in this light makes it appear a much less surprising condition than is usually the case. It would then be the result of a mechanism present in all of us, but pushed to the extreme. Describing crossmodal associations as a form of “weak synaesthesia” (Martino & Marks, 2001) goes in that direction.

Now that consistent crossmodal associations between auditory and both gustatory (Experiment 3.1, 3.2, 3.3) and olfactory stimuli (Belkin et al., 1997; Experiment 3.4) have been demonstrated, one question that arises is to what extent the perception of simultaneously-presented stimuli in two sensory modalities can be affected by the congruency of their matching. Congruent sounds (of eating potato chips or drinking coffee) have been shown to

increase the pleasantness of chip and coffee odours (Seo & Hummel, 2011). It would be interesting to investigate whether this effect would also be found for the musical notes used in the present chapter, which are not in any way related to the sound of consuming food items (see Chapter 5). Both shapes and lighting conditions have been shown to affect the evaluation of taste (Gal, Wheeler, & Shiv, 2007). Moreover, odours have been shown to modulate the rating of tactile stimuli (Demattè, Sanabria, Sugarman, & Spence, 2006), suggesting that crossmodal influences can occur even when the stimuli presented in the two sensory modalities do not constitute features of the same object. Visual stimuli, which have been shown to dramatically modify the perception of olfactory stimuli in some contexts (see, for example, Gottfried & Dolan, 2003; Morrot, Brochet, & Dubourdieu, 2001), may well constitute a somewhat different case, more similar to Seo and Hummel's study. There, the crossmodal associations result from the learning of the colour (or other visual features) of objects, which lead to specific expectations when smelling (or tasting) coloured stimuli (see Shankar, Levitan, & Spence, 2010, for a review). As the crossmodal associations described in the present study occurred with stimuli that do not themselves produce sounds, they cannot work through the same mechanism. Two of the factors that are candidates for driving crossmodal associations between chemosensory and auditory stimuli — pleasantness and familiarity — are further studied in Chapter 4.

4 Chapter 4: The role of familiarity and pleasantness in crossmodal associations between chemosensory stimuli and musical notes

4.1 Introduction

While the presence of crossmodal associations with sounds has been demonstrated and characterised in the experiments reported in Chapter 3, the mechanisms driving them are still largely unexplained at this stage. A few potential factors underlying the crossmodal associations have been suggested, mainly based on the results of PCA. The aim of the experiments reported in this chapter was to study two of these factors in more details, namely familiarity and pleasantness.

If crossmodal associations are learned, familiarity with the stimuli is likely to have an impact on the associations made. Indeed, in the case of crossmodal associations between tastes and odours, presenting pairs of odours and taste solutions modifies the subsequent rating of these odours on taste qualities (sour and sweet; Stevenson et al., 1995). Although odour and taste stimuli are probably rarely presented at the same time as musical notes, a higher familiarity still means they have been perceived more often, with a variety of co-occurring stimuli in other modalities. Moreover, familiarity seems not to be modality-specific, as the neural substrates underlying the feeling of familiarity of odours and musical excerpts largely overlap (Plailly, Tillmann, & Royet, 2007). The familiarity of odours and sounds could thus potentially be matched.

Pleasantness is an essential dimension in the perception and classification of both tastes and odours (Dalton et al., 2008; Zarzo, 2008; see also Section 1.2.7). In the case of food, it is related to the decision of whether items are safe to ingest. Pleasantness is also tightly linked to

the *evaluation* factor suggested by Osgood in his semantic differential method (Osgood, 1952; Osgood et al., 1957) and subsequently used in the context of odours (Dalton et al., 2008).

Experiment 4.1 aimed to replicate Experiment 3.4, which used a set of odours commonly found in wine, but focusing on the effect(s) that familiarity might have on the crossmodal associations that were observed. To this end, a group of participants regularly taking part in wine tasting was recruited, and their performance compared to that of a control group of wine novices. Wine expertise has been shown to have various impacts on performance, depending on the task considered. Overall, experts seem to be better at using language to describe wines, but to have similar olfactory thresholds than novices and to perform no better than novices at identifying wine-related odours (Chollet & Valentin, 2000; Lawless, 1984; Parr, Heatherbell, & White, 2002; see also Section 1.2.8).

Experiment 4.2 focused on the role of pleasantness using chocolate as stimulus, as its pleasantness level varies greatly among people, especially in the case of dark chocolate. Three different kinds of chocolate were compared. One of them (dark chocolate) was then considered on its own in order to try and isolate the role that pleasantness might have when no physical features of the stimulus vary.

Experiment 4.3 was designed to assess how participants would map pitch to a number of dimensions from other domains (amodal or from another modality than audition). The participants were asked to select the direction and rate the appropriateness of the mapping. For example, they were asked whether lightness or darkness was a better metaphor for high pitch and how appropriate the metaphor was. Previous reports (Eitan & Timmers, 2010) showed that many dimensions could be reliably mapped to pitch, including dimensions used by other cultures as a description for pitch. Alongside familiarity and pleasantness, which were the main focus of this chapter, other dimensions were tested in order to uncover further factors that could play a role in the crossmodal associations between pitch and tastes.

4.2 Experiment 4.1

4.2.1 Methods

4.2.1.1 Participants

Twenty-five participants took part in Experiment 4.1 (14 females, aged 21-33 years). Eleven of the participants were members of wine tasting societies and had been taking part in wine tasting events for 1-48 months (M = 18.55, SD = 14.19). The rest of the participants constituted a control group of individuals who stated that they did not drink wine more than 1-3 times a month and had never taken part in a wine tasting event. The experiment was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their senses of smell, and no hearing impairment. The experiment lasted for approximately 60 minutes and the participants were compensated for their time with £10 (UK Sterling) in gift vouchers.

4.2.1.2 Stimuli

Samples from the Nez du Vin aroma kit (Brizard & Co, Dorchester, UK) were used as olfactory stimuli, as in Experiment 3.4. Twenty-four out of the 54 samples from the kit were selected (acacia, almond, apple, apricot, banana, blackberry, blackcurrant, butter, green pepper, honey, lemon, lychee, mushroom, musk, pepper, pine, saffron, smoked, strawberry, thyme, toast, vanilla, violet, and walnut). The samples were presented in small glass bottles identified by a number written on the side of the bottle. The odours were used in the concentration provided in the kit. The auditory stimuli were the same as those used in Experiment 3.1.

4.2.1.3 Procedure

The participants first filled in a questionnaire in order to assess their familiarity with, and knowledge of, wine. They were asked how often they drank wine, whether they had taken part in any wine tasting event before, how long ago they had started regular wine tasting, how many wine tasting events they had attended in the past year, and how many books about wine they had read. The experiment was programmed in E-Prime (version 1.2). The participants were first given the number of the sample that they were to smell. They were then instructed to close

their eyes and were given the bottle by the experimenter. After smelling its content orthonasally, they returned the bottle to the experimenter and were asked to open their eyes to follow the on-screen instructions. First they had to choose a sound to match the smell. The sounds were presented as in Experiment 3.2. After having made their response, they rated the appropriateness of a range of adjectives to describe the smell on 9-point scales. The adjectives rated included three categories: amodal descriptors (complex, familiar, intense, and pleasant), odour descriptors (animal, floral, fruity, nutty, spicy, vegetal, and woody), and taste descriptors (bitter, salty, sour, sweet). All the scales were presented one at a time in a random order, and were anchored by the words *not at all* on the left side, and *extremely so* on the right side. Finally, the participants had to try and identify the sample and note down their response on a sheet listing all sample numbers. The 24 olfactory stimuli were presented once in a random order.

4.2.2 Results

4.2.2.1 Ratings and identifications

The responses to the questionnaire about wine familiarity and knowledge demonstrated that there was great variability within groups. Both the wine taster and the non-wine taster groups were thus each divided in two subgroups. For the non-wine tasters, the frequency of wine drinking was used to define the subgroups: The “unfamiliar” subgroup was composed of those participants who reported drinking wine no more often than 1-2 times a year; the “familiar” subgroup included those participants who reported drinking wine several times a year, up to 1-3 times a month. For the wine tasters, the number of wine tasting events attended in the past year was used to define subgroups: The “amateur” subgroup was composed of those participants who reported having attended up to 10 events; the “experienced” subgroup included those participants who had attended more than 10 events in the past year.

The ratings of the four subgroups were compared using one-way ANOVAs. All adjectives were used differently by the subgroups, with the exception of animal, complex, and intense (see Table 4.1). Post-hoc *t* tests (Bonferroni corrected) highlighted a variety of rating behaviours: Unsurprisingly, the unfamiliar subgroup rated the odours as less familiar; however, there was no significant difference in the rating of familiarity among the other subgroups. There was a tendency in the experienced subgroup to give lower ratings on all odour and taste descriptors.

Table 4.1: Effect of wine familiarity on ratings (amodal, olfactory, and gustatory descriptors) of odours in Experiment 4.1 **(**Means and one-way ANOVAs).

	Subgroups					
	1	**2**	**3**	**4**	**F**	***p***
Complex	5.21	5.09	5.46	5.03	1.34	.260
Familiar	4.71	5.80	6.13	5.87	10.83	< .001
Intense	5.26	5.77	5.76	5.55	2.12	.097
Pleasant	5.04	4.96	5.80	5.51	5.03	.002
Animal	2.47	2.60	2.31	2.04	1.91	.126
Floral	4.39	4.69	4.55	3.70	3.78	.011
Fruity	4.52	4.92	4.71	3.90	3.05	.028
Nutty	2.89	3.25	4.25	2.98	11.42	< .001
Spicy	2.85	3.58	3.53	3.39	3.45	.016
Vegetal	4.43	4.89	4.13	2.67	23.37	< .001
Woody	4.14	4.09	4.59	3.23	7.07	< .001
Bitter	3.28	3.06	4.13	1.78	25.96	< .001
Salty	3.22	3.10	2.58	1.89	13.01	< .001
Sour	3.38	2.80	3.36	1.86	16.05	< .001
Sweet	4.59	5.24	5.53	4.21	7.29	< .001

Participants' responses when identifying the odours were classified into four categories: exact identification, identification of a closely related item (for example, naming another citrus fruit for lemon, or another berry for strawberry), identification of the broad category (e.g., fruit, plant), and incorrect identification. The participants were able to correctly (and exactly) identify the olfactory stimulus in 11.5% of the cases. In a further 27.0% of cases, they identified either a closely related item (6.5%) or the category of the stimulus (20.5%) correctly. The percentage of correct responses was computed for each participant (the exact identification and identification of a closely related item were considered correct). There was no effect of wine expertise on performance (one-way ANOVA, $F(3,21) = 1.14$, $p = .36$).

4.2.2.2 Pitch

A mixed ANOVA was conducted in order to assess whether the odours or familiarity with wine affected the choice of pitch. The results indicated that the odours affected the choice of pitch, $F(23, 483) = 5.11$, $p < .001$ (see Figure 4.1). Familiarity with wine (measured by subgroup) had no main effect on the choice of pitch, $F(3, 21) = 1.32$, $p = .29$, and there was no interaction between familiarity and odour, $F(69, 483) < 1$, *n.s*. The range of chosen pitch (53.8-72.2, in MIDI note numbers) was very similar to that found for the odours in Experiment 3.4 (54.6-72.3).

4.2.2.3 Instruments

Chi-square tests for goodness of fit were conducted to determine which odours induced a distribution of instrument choice that was significantly different from that expected by chance. Out of the 24 odours used, 10 gave rise to significant preferences in the choice of instrument (see Table 4.2 and Figure 4.2).

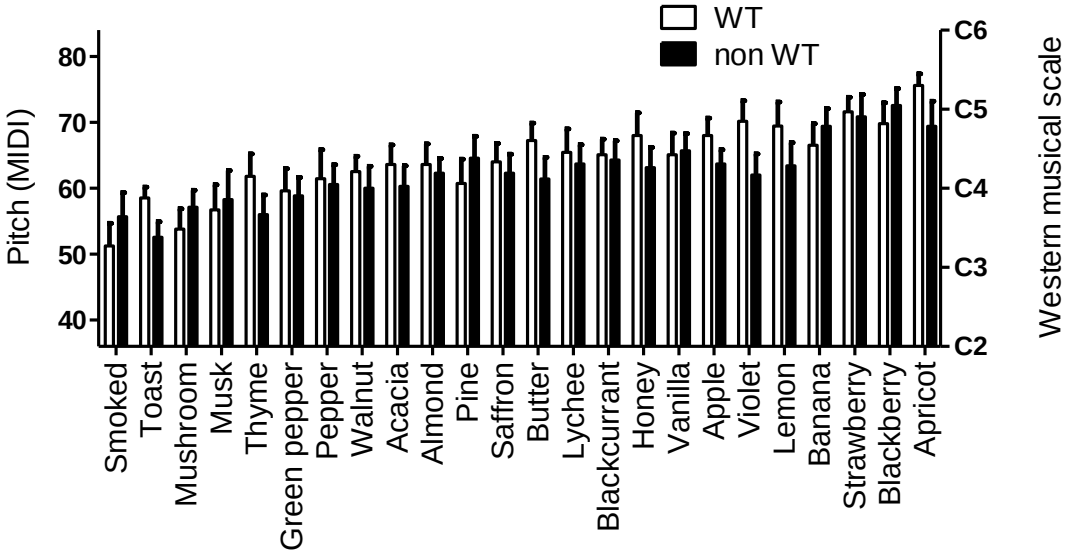


Figure 4.1: Mean pitch matched to each odour by the wine taster group (WT) and the control group (non WT) in Experiment 4.1. MIDI note numbers were used to code the pitch of the chosen notes. Western musical scale notation is shown on the right-hand y-axis. High-pitched notes were preferred for fruits. Error bars represent the SEM.

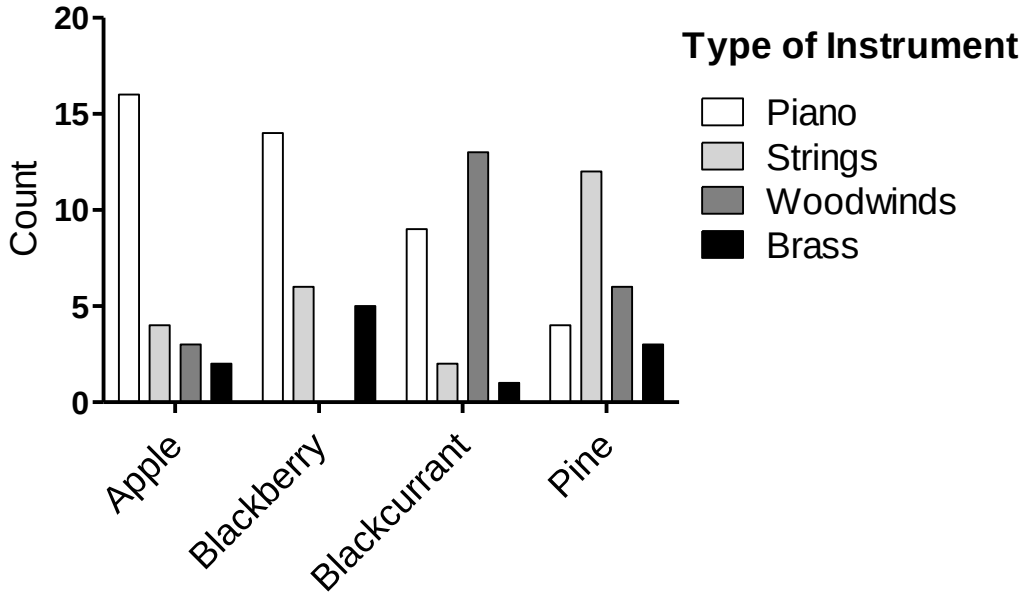


Figure 4.2: Examples of instrument types matched to the odours in Experiment 4.1. Maximum count is 25.

Table 4.2: Chi-square for goodness of fit (df = 3) for the choice of instruments matched to each odour in Experiment 4.1. Significant results ($p < .05$) are in bold.

	χ^2	*p*
Acacia	2.36	.501
Almond	**11.96**	**.008**
Apple	**20.60**	**< .001**
Apricot	**10.04**	**.018**
Banana	**10.36**	**.016**
Blackberry	**16.12**	**.001**
Blackcurrant	**15.80**	**.001**
Butter	3.96	.266
Green pepper	3.00	.392
Honey	3.96	.266
Lemon	3.96	.266
Lychee	1.40	.706
Mushroom	4.28	.233
Musk	5.24	.155
Pepper	2.36	.501
Pine	**7.80**	**.050**
Saffron	1.40	.706
Smoked	0.76	.859
Strawberry	**9.72**	**.021**
Thyme	3.96	.266
Toast	**8.12**	**.044**
Vanilla	**9.08**	**.028**
Violet	1.40	.706
Walnut	2.36	.501

4.2.2.4 Effects of ratings on the choice of musical notes

The correlations between the choice of pitch and all ratings were significant in at least one subgroup, with the exception of intense and sour (see Table 4.1). However, there were some differences between the subgroups. The participants in the fourth subgroup (the more experienced wine tasters) showed no correlations between their choice of pitch and their ratings of either the familiarity or the pleasantness of the odours.

Table 4.3: Pearson correlation coefficients (and *p* values) between the choice of pitch and the various ratings (amodal, odour, and taste descriptors) for each subgroup (1: unfamiliar, 2: familiar, 3: amateur, and 4: experienced) in Experiment 4.1.

Subgroup	**1**	**2**	**3**	**4**
Rating				
Complex	-.194	-.116	-.214	-.187
	.012	.133	< .001	.041
Familiar	.126	.328	.283	.052
	.104	< .001	.001	.573
Intense	-.046	.115	-.033	.062
	.558	.139	.692	.503
Pleasant	.323	.278	.368	.113
	< .001	< .001	< .001	.218
Animal	-.239	-.171	-.380	-.295
	.002	.026	< .001	.001
Floral	.155	.262	.337	.245
	.045	.001	< .001	.007
Fruity	.167	.292	.464	.329
	.031	< .001	< .001	< .001
Nutty	-.066	-.169	-.282	-.175
	.394	.028	.001	.056
Spicy	-.135	-.130	-.201	-.052

	.081	.094	.016	.573
Vegetal	-.089	-.144	-.241	-.233
	.250	.062	.004	.011
Woody	-.277	-.352	-.402	-.227
	< .001	< .001	< .001	.013
Bitter	-.349	-.196	-.390	-.365
	< .001	.011	< .001	< .001
Salty	-.210	-.150	-.305	-.218
	.006	.052	< .001	.017
Sour	-.043	.000	-.152	.081
	.580	.999	.069	.381
Sweet	.251	.446	.465	.380
	.001	< .001	< .001	< .001

Mixed ANOVAs were used to determine whether odours associated with different instruments were rated differently by participants, with the expertise group as a between-subject variable. The choice of instrument led to difference in pleasantness ratings ($F(3,57) = 20.38$, $p < .001$), but did not affect the familiarity ratings ($F(3,57) = 1.96$, $p = .13$). The interaction between the choice of instrument and the expertise groups was not significant in both cases ($F(9,57) = 1.39$, $p = .21$, $F(9,57) = 1.12$, $p = .37$).

4.2.3 Discussion

Rather surprisingly, wine tasters in this experiment did not exhibit a very different pattern of performance from the non-wine tasters. In particular, they were no better at identifying the odours (although see Parr et al., 2002, for similar results). This might be due to a number of factors, the main one being that none of the participants had a professional training in wine knowledge. Another factor could have been that the orthonasal odours used, while being

commonly found in wine, were all of natural products that could have been encountered by participants in a number of other situations. That said, there are still a number of interesting differences between subgroups highlighted by the results of the present experiment. First, the results seem to indicate that regular wine drinking (from several times per year) is enough to increase the familiarity with the odours, and that additional experience with wine does not appear to increase the ratings further. However, only wine tasters (amateur and experienced subgroups) rated the odours as being more pleasant. One has to be careful when interpreting these ratings, as they might be subject to response bias, the participants being informed before the experiment that the odours used were found in wine. There is a tendency for the experienced subgroup to give overall lower ratings for odour and taste descriptors than the other subgroups, although they did not rate the odours as less intense. This might result from a more precise use of the adjectives provided.

In terms of the crossmodal associations between the odours and musical notes, previous results (see Experiment 3.4) were replicated with this new set of odours. Wine knowledge did not affect the choice of pitch that was matched to odours. However, the experienced wine tasters' choices were not correlated with other ratings in the same way as for the other subgroups: Their choice of pitch was not correlated with either their familiarity or pleasantness ratings.

To conclude, knowledge of and familiarity with the stimuli do not seem to influence the crossmodal associations that exist between chemosensory and auditory stimuli, at least in the present case, although these factors influence the representation of the stimuli in subtle ways.

4.3 Experiment 4.2

4.3.1 Methods

4.3.1.1 Participants

54 participants took part in Experiment 4.2 (33 females, aged 18-38 years). The experiment was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their senses of taste and smell, and no hearing impairment. The experiment lasted for approximately 5 min.

4.3.1.2 Stimuli

Three types of chocolate were used: dark chocolate (85% cocoa, Lindt), milk chocolate (30% cocoa, Lindt), and marzipan-filled chocolate (37% cocoa in the chocolate, Frey). The samples weighed approximately 5 g (dark and milk chocolate) or 6.7 g (marzipan-filled chocolate).

The auditory stimuli were the same as those used in Experiment 3.1.

4.3.1.3 Procedure

The experiment was programmed in E-Prime (version 1.2). The participants were first given the number of the sample that they were to taste. They were then asked to close their eyes and were given the chocolate by the experimenter. As soon as they had placed the chocolate in their mouth, they were asked to open their eyes again so that they could follow the on-screen instructions. The sounds were presented on four scales corresponding to the four types of instruments. Pitch increased along the scales (horizontally), the direction was randomly chosen for each trial. The sounds could be heard by clicking on the scale. The participants were free to click on as many of the sounds as they wished before making their choice. After having made their response, they rated the bitterness, sweetness, and pleasantness of the sample on 9-point scales. These ratings were made in a random order. All of the scales were anchored by the words *not at all* on the left side, and *extremely so* on the right side. The three types of

chocolate were presented once in a random order. In between samples, participants were instructed to rinse their mouth with tap water and eat a piece of cream cracker (Jacob's, UK).

4.3.2 Results

4.3.2.1 Pitch

A repeated-measures ANOVA, with Greenhouse-Geisser correction, was conducted in order to assess whether there were any differences between the average pitch matched to the three types of chocolate. As expected, the results indicated that the participants matched the three types of chocolate to pitch differently, $F(1.96, 104.12) = 22.41$, $p < .001$. Post-hoc *t* tests (Bonferroni-corrected) revealed that all three types of chocolate were significantly different from the other two (see Figure 4.3).

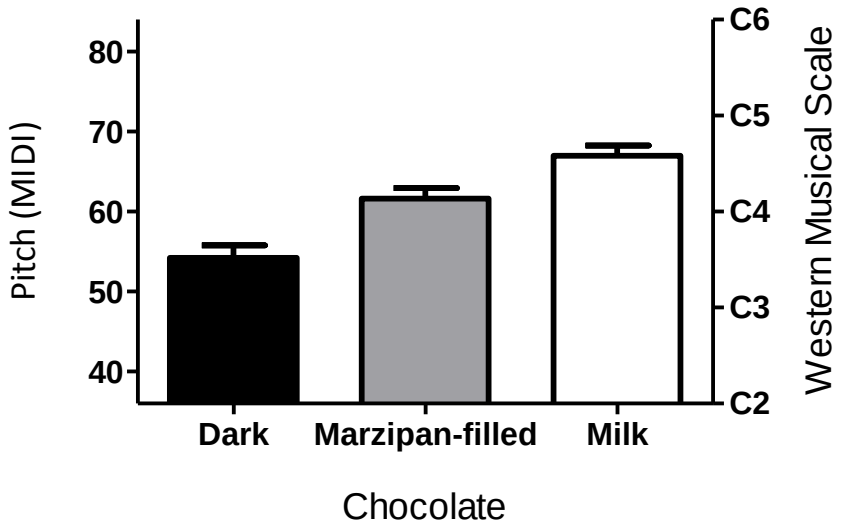


Figure 4.3: Mean pitch matched to each type of chocolate in Experiment 4.2. MIDI note numbers were used to code the pitch of the chosen notes. Western musical scale notation is shown on the right-hand Y-axis. Error bars indicate the SEM.

4.3.2.2 Types of instrument

Chi-square tests for goodness of fit were conducted in order to determine which types of chocolate induced a distribution of instrument choice that was different from that expected by chance. Only the milk chocolate gave rise to significant preferences in the choice of instrument ($\chi^2(3, N = 54) = 48.07$, $p < .001$, see Figure 4.4).

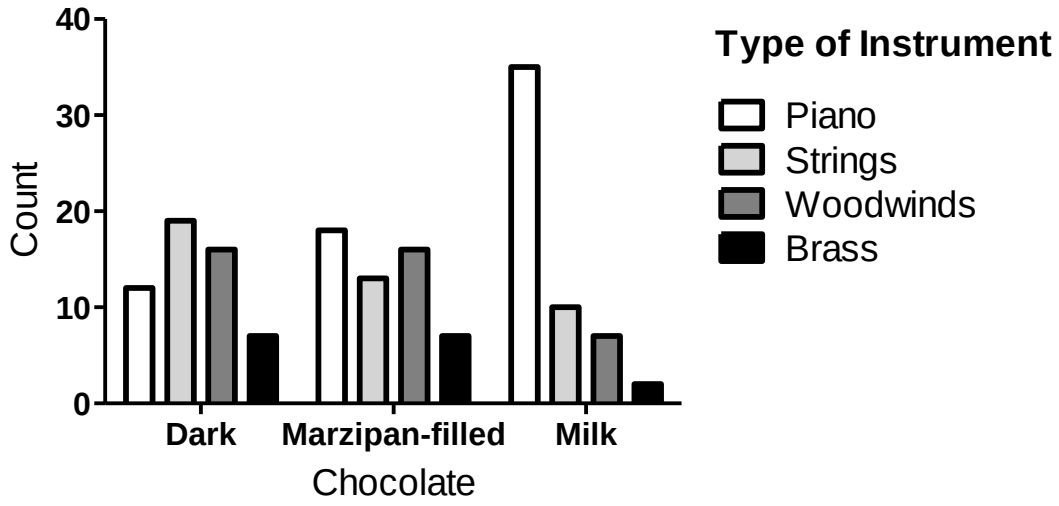


Figure 4.4: Choice of instrument as a function of the type of chocolate presented in Experiment 4.2. The total count per category is 54.

4.3.2.3 Overall effects of ratings on choice of musical notes

The correlations between the choice of pitch and the ratings of bitterness, sweetness, and pleasantness were all significant (see Table 4.4).

Table 4.4: Pearson correlation coefficients between the choice of pitch and the various ratings for all stimuli in Experiment 4.2. Bold indicates significant correlations: * $p < 0.05$, ** $p < .01$.

	Bitter	Pleasant	Sweet	Pitch
Bitter		**-.478****	**-.849****	**-.408****
Pleasant	**-.478****		**.530****	**.185***
Sweet	**-.849****	**.530****		**.375****
Pitch	**-.408****	**.185***	**.375****	

The bitterness, sweetness, and pleasantness ratings were compared for stimuli associated with different types of instruments using one-way ANOVAs. The ratings on all three scales varied with the choice of instrument ($F(3,120) = 4.76$, $p = .004$ for bitterness; $F(3,120) = 9.68$, $p < .001$ for pleasantness; $F(3,120) = 3.29$, $p = .023$ for sweetness; see Figure 4.5)

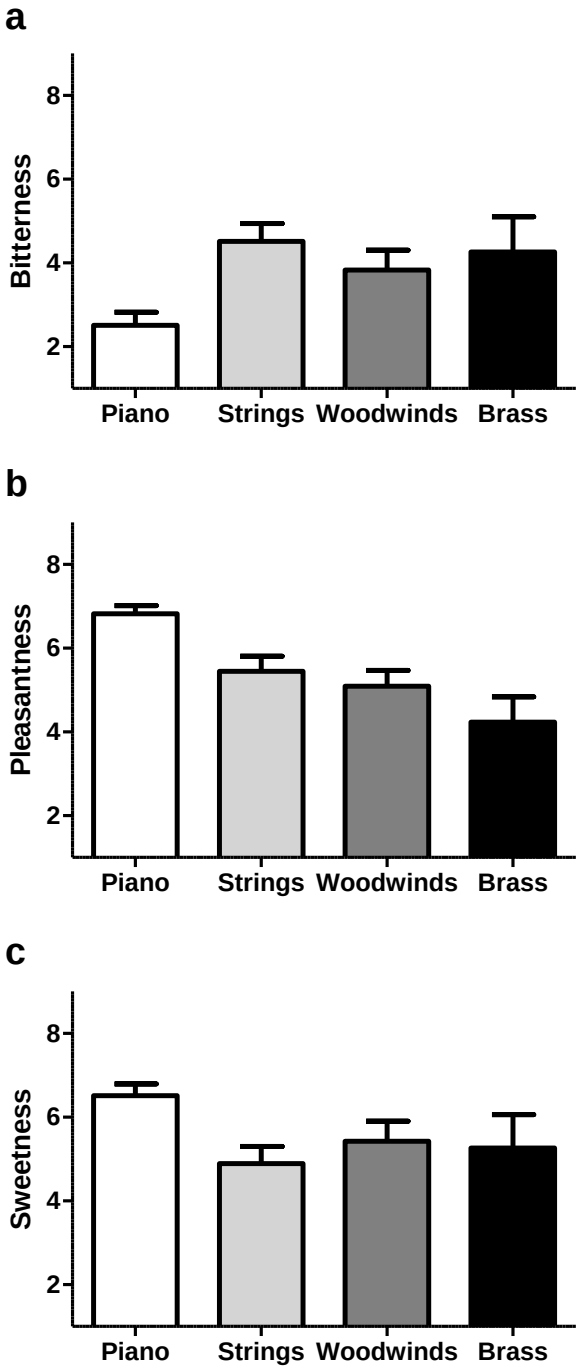


Figure 4.5: Ratings of bitterness (a), sweetness (b), and pleasantness (c), as a function of the choice of instrument in Experiment 4.2. Error bars represent the SEM.

4.3.2.4 Effects of ratings on choice of musical notes for a single stimulus

Pleasantness ratings ranged from 1 to 9 for both the dark and marzipan-filled chocolate samples (*M* = 4.63, *SD* = 2.35, *M* = 5.89, *SD* = 2.10), while the range for milk chocolate only spanned from 4 to 9 (*M* = 7.07, *SD* = 1.21). As it had the highest standard deviation of the three

types of chocolate, dark chocolate was chosen to explore the role of pleasantness in the choice of pitch. The correlation between the pleasantness ratings and the chosen pitch revealed that these two values were not significantly related, r = -.18, N = 54, p = .20, two-tailed (see Table 4.5).

Table 4.5: Pearson correlation coefficients between the choice of pitch and the various ratings for the dark chocolate in Experiment 4.2. Bold indicates significant correlations: ** $p < .01$.

	Bitter	Pleasant	Sweet	Pitch
Bitter		-.245	-.219	.106
Pleasant	-.245		**.505****	-.179
Sweet	-.219	**.505****		-.081
Pitch	.106	-.179	-.081	

A one-way ANOVA was conducted to compare the pleasantness ratings of participants as a function of the instrument they matched to the stimulus. The results indicated that dark chocolate was rated differently when associated with different instruments, $F(3,50) = 2.80$, p = .049.

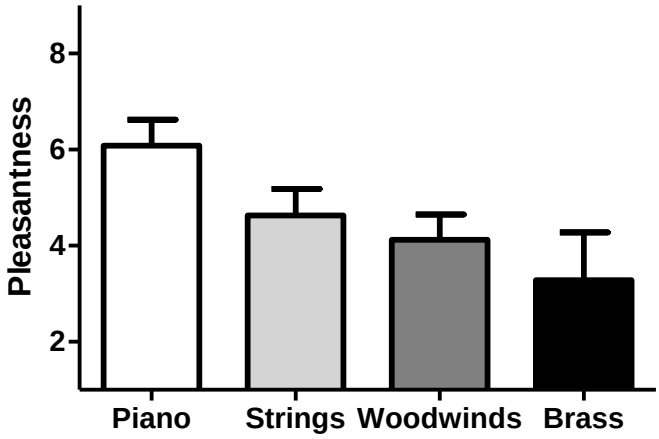


Figure 4.6: Pleasantness ratings for the dark chocolate in Experiment 4.2 as a function of the choice of instrument.

4.3.3 Discussion

The existence of crossmodal associations between flavours and musical notes was confirmed with stimuli that were very similar to each other (see also Experiment 3.3 with crisps). These crossmodal associations can thus arise from relatively subtle differences between stimuli belonging to the same category (in this case chocolate).

Pleasantness ratings for the stimuli were correlated with the frequency of the pitch chosen to match them. However, when only a single stimulus (dark chocolate) was considered, differences in ratings of pleasantness did not affect the choice of pitch. This result, while surprising considering the results presented in Chapter 3, is in line with the latest results from Eitan and Timmers (2010). In their study, participants did not agree on which direction the pleasant-unpleasant scale should be used as a metaphor for high-low pitch (see also Experiment 4.3).

In contrast to pitch, there was still an effect of pleasantness ratings on the choice of instruments when an individual stimulus was considered. These results therefore suggest that the choice of pitch and instrument class were independent, and driven by different factors. While subjective pleasantness impacts on the choice of instrument, the participants' choice of pitch seems to rely on other features of the stimulus. However, individual differences in bitterness and sweetness ratings for a single stimulus also failed to explain the choice of pitch. It could be that the variations in chosen pitch for a single stimulus are random and do not depend on individual variations of subjective ratings.

The consistent correlation between sweetness and pleasantness ratings, found even when a single stimulus is considered, is not surprising: It is well-known that sweetness is innately liked and induces an orofacial reflex that facilitates ingestion (lip suck, Steiner, 1974; see also Weiland, Ellgring, & Macht, 2010). Moreover, the word *sweet* is used in many other

contexts than taste perception, to refer to something pleasant (*Collins English dictionary and thesaurus*, 2000).

It could be argued that no correlations are found between the choice of pitch and ratings when a single stimulus is considered because of the loss of statistical power, given that only a third of the trials were considered. However, not only do the correlations between pitch and ratings lose their significance when only dark chocolate is considered, they actually change direction. By contrast, this does not happen for correlations between the other ratings (see Table 4.5).

These results therefore confirm the role of pleasantness in the matching of musical instruments to tastes/flavours, but rule it out as a leading factor mediating the crossmodal associations between tastes/flavours and pitch.

4.4 Experiment 4.3

4.4.1 Methods

4.4.1.1 Participants

38 participants took part in Experiment 4.3 (17 females, aged 26-36 years). None of the participants from Experiment 4.3 had taken part in any of the previous experiments.

4.4.1.2 Procedure

The participants received a paper questionnaire containing 11 pairs of antonyms (see Table 4.7 for the list). For each pair, half of the participants were asked to choose which adjective was the best metaphor for high pitch. The other half of the participants were asked the same question about low pitch. They were also all asked to rate the appropriateness of the pair of adjective as a metaphor for pitch on a line scale, anchored with *not well at all*, and *extremely well*. The order of the adjectives within each pair was counterbalanced across the participants.

4.4.2 Results

Chi-square tests for independence were conducted to assess whether asking participants to select the adjective for high or low pitch, or the order of presentation within the antonym pairs affected the responses they gave. The results indicated that their choice was independent of both factors. All questionnaires were thus further analysed together. The proportion of participants choosing an adjective to represent high (vs. low) pitch was significantly higher than chance for sharp (vs. blunt), light (vs. dark), crunchy (vs. creamy), clean (vs. dirty), and fresh (vs. stale) (see Table 4.7 for detailed results). A repeated-measures ANOVA, with Greenhouse-Geisser correction, was conducted in order to assess whether there were any differences between appropriateness ratings for the 11 pairs of adjectives. The results indicated that the participants rated the 11 pairs of adjectives differently, $F(6.06, 212.07) = 11.48$, $p < .001$ (see Table 4.7).

Table 4.6: Proportion of participants choosing the first adjective of the pair as the best metaphor for high pitch (H) in Experiment 4.3, *p* values for chi-square tests assessing whether the choice of one adjective is significantly different from 50% (df = 1), and mean of appropriateness ratings (scales ranged from 0, *not at all appropriate*, to 8, *extremely appropriate*) for each pair of adjectives.

	H	*p*	Appropriateness
Sharp-blunt	.95	< .001	6.27
Light-dark	.90	< .001	5.61
Rough-smooth	.65	.071	4.38
Unpleasant-pleasant	.53	.746	4.14
Sour-bitter	.60	.250	4.13
Simple-complex	.55	.516	3.86
Crunchy-creamy	.79	< .001	3.73
Clean-dirty	.84	< .001	3.69
Fresh-stale	.74	.004	3.23
Sweet-salty	.61	.194	3.18
Unfamiliar-familiar	.66	.052	2.72

4.4.3 Discussion

In accordance with recent research (Eitan & Timmers, 2010), the results of Experiment 4.3 confirm that some dimensions are consistently associated with pitch, and are felt to be an appropriate description of pitch: Sharp-blunt, light-dark, and, although it did not reach significance at $\alpha = .05$, rough-smooth fit into that category. Other dimensions, such as pleasantness, are felt to be a somewhat appropriate description for pitch, but there is no agreement on the direction it should be associated with. There is a third category of dimensions that are not felt to be appropriate to describe pitch, but on which participants agree nonetheless when it comes to choosing the direction in which the comparison makes the more

sense. Unfamiliar-familiar can be counted in that category, as there is a clear trend for *unfamiliar* to be preferentially associated with high pitch (p = .052).

Surprisingly, the participants did not agree on how the sour-bitter and sweet-salty pairs should be associated with pitch. It might be that the crossmodal associations uncovered in previous experiments are largely unconscious, and thus only appear in implicit tasks, or when the participants can both hear the sounds, and taste (and/or smell) the chemosensory stimuli, neither of which was the case in the present experiment.

4.5 General discussion

The results of Experiment 4.1 indicate that familiarity with the stimuli does not play a significant role in the crossmodal associations that exist between odours and musical notes, although it changes the way in which odours are rated in more subtle ways. However, it should once again be noted that even participants in our most experienced subgroup had at most a few years of wine tasting practice. We cannot rule out the possibility, therefore, that testing wine professionals might have led different results. It could also have been interesting to train participants with novel odours in order to have a better control over their level of familiarity.

Another potential issue is that perceived familiarity most probably did not vary much for single musical notes, as it would for musical excerpts. One could expect a more prominent role of familiarity in crossmodal associations between chemosensory stimuli and music (Mesz et al., 2011), as the neural substrates activated by the feeling of familiarity of odours and musical excerpts has been demonstrated to overlap (Plailly et al., 2007). Stimuli from both sensory modalities could thus be matched based on their familiarity.

The results of Experiment 4.2 give clearer answers as to the role of pleasantness in the crossmodal associations. The choice of instruments does indeed seem to be largely based on a matching between the pleasantness of tastes and notes. The choice of pitch, on the other hand, seems to be independent of the pleasantness rating, as shown when a single stimulus is

considered. This is confirmed by the results of Experiment 4.3, where participants did not agree on whether high or low pitch should be matched to pleasantness. Experiment 4.3 also suggests that other features of the stimuli, such as crunchiness and creaminess, should be explored, as there was a strong agreement among participants that crunchiness should be matched to high pitch (see also Vickers, 1984; Zampini & Spence, 2004), while creaminess was a better description of low pitch. Although worth investigating, this mapping could not explain the results of Experiment 4.2, where the creamier milk chocolate was associated with higher pitch than the crunchier dark chocolate. It would also be interesting to compare further the potential factors involved in these crossmodal associations with the factors from semantic differential scaling, i.e., *evaluation* (good-bad), *potency* (strong-weak), and *activity* (active-passive; see Osgood et al., 1957). Evaluation corresponds to the pleasantness ratings, and has been shown to influence the choice of instrument, but not of pitch. Potency, as measured by our intensity ratings, does not affect the choice of musical note (although it would probably affect the choice of loudness, if participants were allowed to choose it). Finally, the creamy-crunchy dimension mentioned above could be mapped to the activity factor. How it may relate to the choice of pitch, however, remains unclear (although see Eitan & Timmers, 2010, which suggests that *active* is associated with high pitch, while *passive* is associated with low pitch).

To conclude, while the choice of instrument seem to be largely based on a pleasantness matching between chemosensory and auditory stimuli, the choice of pitch remains largely unexplained: It is unlikely to be based on statistical learning of co-occurrence of stimuli, and there is no obvious semantically-mediated mapping.

5 Chapter 5: The influence of auditory stimuli on chemosensory perception

5.1 Introduction

The results of Chapter 4 shed some light on the factors underlying the crossmodal associations that exist between chemosensory and auditory stimuli, even though they might have raised as many questions as they provided answers. The experiments reported in the present chapter focused on a different issue. They were designed to investigate whether auditory stimuli presented simultaneously with chemosensory stimuli could influence the perception of the latter.

This issue is of obvious practical importance given that it could open-up new avenues for modifying the perception of foodstuffs in consumers and/or patients. It has already been demonstrated that music can influence the behaviour of consumers in a variety of settings (see Section 1.4.2). Moreover, recent studies have proven that background noise can reduce the perceived intensity of taste qualities (Woods et al., 2011), as well as impair a participant's performance in an odour discrimination task (Seo et al., 2011). The presentation of auditory stimuli has also been shown to modulate ratings of odour pleasantness (Seo & Hummel, 2011). However, the specific effects of crossmodal congruency between sounds and tastes (or odours) on taste qualities have not been studied to date.

On top of these practical considerations, a better understanding of how auditory and chemosensory perception interact might help determine the level at which these crossmodal associations occur, and thus also be of theoretical importance. Due to time constraints, the experiments presented in this chapter are only preliminary and were meant to suggest directions for future research more than necessarily to provide definitive answers to the

questions posed. As such, they could be improved in a number of ways. Nevertheless, that said, they still provide useful information and constitute a good starting point for future research.

Experiment 5.1 studied the effect of listening to soundtracks designed to correspond to either bitter or sweet tastes on the perception of a food item (cinder toffee). The food item was designed to be both bitter and sweet. The participants rated the pleasantness of the toffee, the position in the mouth where they experienced the taste, as well as the bitterness of the toffee on a bitter-sweet continuum. The participants tasted the food in a naturalistic way.

Experiment 5.2 presented single notes (high-pitched, low-pitched, or a burst of white noise) with either bitter (coffee) or sour (lemon) odours. The bitterness, sourness, and intensity of the odours were rated by the participants. The odours were presented through a custom-build olfactometer, allowing for a much more precise control of stimulus timing, but making the conditions less naturalistic than in Experiment 5.1.

The two experiments reported in the present chapter thus offer a glimpse of the influence of sounds on chemosensory perception in two very different ways: using a complex food item under naturalistic conditions in Experiment 5.1, and using orthonasally-presented odours in a much more controlled setting in Experiment 5.2.

5.2 Experiment 5.1

5.2.1 Methods

5.2.1.1 Participants

Twenty participants took part in Experiment 5.1 (12 females, aged 17-33 years). The participants gave their informed consent, reported no cold or other impairment of their senses of smell and taste, and no hearing impairment. The participants were informed that they would be asked to taste toffee. The experiment lasted for approximately 10 minutes and the participants were compensated for taking part in the study with a £5 (UK Sterling) gift voucher.

5.2.1.2 Stimuli

The cinder toffee used in the present study was prepared at The Fat Duck experimental research kitchen, Bray, UK. The recipe utilised sugar, butter, golden syrup, treacle, salt, and sodium bicarbonate.

The auditory stimuli were created by a sonic branding agency (Condiment Junkie), using the Logic 9 music production software, installed on a Mac G5. All of the sounds were presented in the key of F. The bitter soundtrack consisted of a blend of sinewave-based synthesised tones generated by the Sculpture Modelling synth and ES2 synth plug-ins, pitched at F2 (MIDI note 41) and C3 (MIDI note 48). These sounds were overlaid with a single trombone note also played at F2, and a low frequency rumble created by passing a field recording of car traffic in a tunnel through a low pass filter. The main element of the sweet soundtrack was created from the Yamaha Grand piano plug-in, passed through a Space Designer reverb unit set to 100% wet and 10% dry (so mostly only the reverb was heard). The notes moved in legato through the F scale pitched around C4 - C6 (MIDI notes 60 - 84). This sound was overlaid with a sinewave-based synthesised tone generated by the Sculpture Modelling synth plug-in in the same pitch, as well as abstractions of the piano sound created by resampling and reversing the sound several times. These soundtracks are available at: www.condimentjunkie.co.uk/bittersweet.

5.2.1.3 Procedure

The experiment was conducted with participants sitting at a table in a darkened experimental booth. The participants sat in front of a computer monitor and responded by using the mouse. The auditory stimuli were presented over Beyerdynamic headphones at a level of approximately 70 dB. The participants were presented with four small pieces of the cinder toffee (approximately 0.3 grams) to taste. Auditory stimuli were presented at the same time that the toffee samples were given to the participants, i.e., a few seconds before they tasted the samples.

The participants were given three response scales to score for each of the four samples. They were asked a question in relation to each scale, namely: Is the food bitter or sweet? How much do you like the taste/flavour? Where in your mouth do you experience the flavour? The participants responded using a 9-point computer-based scale. Each scale was anchored with a pair of terms (*bitter (earthy)* / *sweet*, *back of the mouth* / *tip of tongue*, *not at all* / *very much*). The scales were presented in a random order. Each participant tasted four samples in total. Each participant tasted the cinder toffee twice with each of the soundtracks. The order of presentation of the soundtracks was randomized.

5.2.2 Results

The mean ratings on each scale (see Figure 5.1) were analysed using a separate paired-samples *t* test. There was a significant effect on the bitter-sweet scale, on which participants rated the toffee as less sweet when presented with the "bitter" soundtrack (M = 4.70, SD = 1.52) than when it was presented with the "sweet" soundtrack (M = 5.40, SD = 1.29), $t(19) = 2.284$, $p = .034$, $r = .46$. However, no such effect was found on either of the other response scales (for position, M = 4.55, SD = 1.79 with the "bitter" soundtrack, M = 5.00, SD = 1.29 with the "sweet" soundtrack, $t(19) = 1.564$, $p = .134$, $r = .34$; and for pleasantness, M = 5.30, SD = 1.72 with the "bitter" soundtrack, M = 5.75, SD = 1.40 with the "sweet" soundtrack, $t(19) = 1.027$, $p = .317$, $r = .23$).

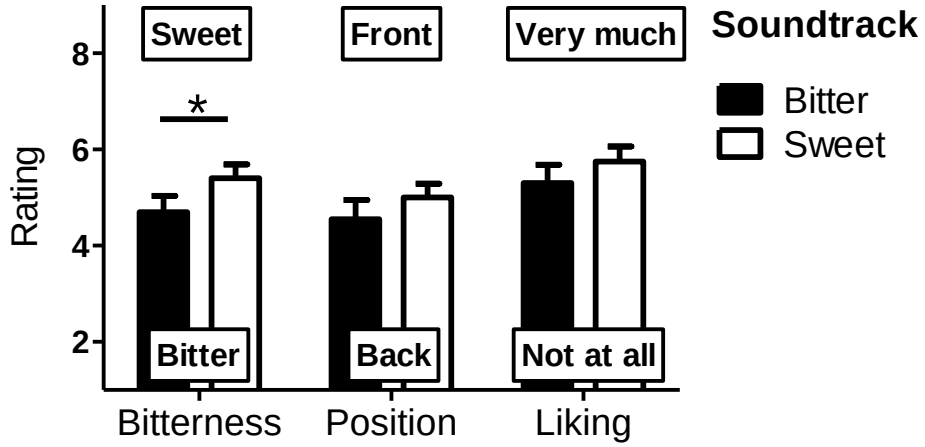


Figure 5.1: The results of Experiment 5.1 highlighting the effect of the auditory soundtrack ("bitter" vs. "sweet") on participants' ratings on the bitter-sweet scale, the back-front (of mouth) scale, and the hedonic rating scale. The asterisk highlights a significant difference between the conditions ($p < .05$). The error bars represent the SEM.

5.2.3 Discussion

The results demonstrate that the taste of a foodstuff can be systematically altered by playing a soundtrack that is crossmodally associated with the taste in question (cf. Holt-Hansen, 1976). Based on the results of Experiment 3.1, two soundtracks were created for use in the present experiment. One soundtrack was designed to complement the bitter taste present in the foodstuff (cinder toffee), while the other was designed to match the sweet taste instead. The "bitter" soundtrack contained a predominance of low-pitched sounds, whereas the "sweet" soundtrack was comprised of sounds having a higher pitch. As predicted, the results demonstrated that participants rated the sweet taste of the cinder toffee as being significantly more intense (that is, their responses were significantly closer to the sweet end of the response scale) when listening to the "sweet" soundtrack than when listening to the "bitter" soundtrack. These results therefore provide the first robust empirical demonstration that the crossmodal congruency of the background music/soundtracks that we listen to really can influence the taste of the food we eat and presumably also the beverages we drink (see also Ferber & Cabanac, 1987; Woods et al., 2011).

Although there were potentially interesting numerical trends in the data reported for the other two response scales they failed to reach statistical significance. It is at least possible that these trends would have reached statistical significance had a much larger number of participants been tested. It is perhaps also worth noting, in passing, that increased bitter ratings were also associated with a trend for participants to localise the flavour experience further toward the back of their mouth. However, given that these response scales failed to deliver significant results in the present experiment, they will not be discussed further here.

The results of the present experiment go beyond the experiments reported in Chapter 3 demonstrating the existence of crossmodal associations between tastes/flavours/oral-somatosensory experiences and various attributes of auditory stimuli (see also Holt-Hansen, 1968; Mesz et al., 2010; Rudmin & Capelli, 1983), by showing that the actual taste of a foodstuff can be altered by playing auditory stimuli that (on the basis of laboratory research) either correspond crossmodally or not.

At this stage, one can do little more than speculate as to the neural mechanisms underlying the crossmodal effect of sound on taste perception reported here. However, two possibilities immediately spring to mind, one in terms of multisensory integration, the other in terms of expectancy effects and "sensation transference" (Cheskin, 1972). The idea that the soundtrack may have influenced participants' perception of the taste of the cinder toffee because of the multisensory integration of the two component unimodal stimuli (see Calvert, Spence, & Stein, 2004) is supported by anecdotal reports from chefs who experienced a change in taste when the soundtracks were changed while tasting the toffee. That said, the onset of the auditory and gustatory stimuli occurred at different times, and were experienced in different locations. This should presumably have reduced the likelihood that these two signals would have been integrated.

The second hypothesis is that the soundtrack, which was presented at the same time as the toffee samples, and, importantly, could be heard a few seconds before the participants actually started to taste the sample, may have induced sensory expectations (possibly subconscious) that, in turn, influenced the perceived taste of the food that was subsequently consumed. This explanation for the data is supported by previous research underlining the powerful effects that expectations can have on sensory evaluations (e.g., see Deliza & MacFie, 1996, for a review). The idea here is that when a stimulus is presented in one sensory modality it may prime those sensory attributes that are crossmodally associated with it. Such a crossmodal priming effect may then affect a participant's perception and responses when another stimulus is presented subsequently. Thus, in the case of the present study, the lower-pitched soundtrack may have set up an unconscious expectation that primed bitterness in the minds of the participants.

Here, it is worth noting that such effects can also be described in terms of Louis Cheskin's (1972) idea of "sensation transference". Cheskin argued that the sensory features of the atmosphere in which we evaluate a product (not to mention also the sensory features of the packaging in which the product is presented), be it a food item or something else, can be transferred such that they influence a person's impression of the sensory qualities/attributes of the thing being evaluated (see also Spence & Piqueras-Fiszman, in press). Importantly, when questioned directly, Cheskin found that most consumers would vociferously deny the influence of such product extrinsic factors on their judgments. Nevertheless, indirect tests demonstrated that such product extrinsic (or atmospheric) factors were influencing people's perception (see also Gal et al., 2007).

While it is certainly true that previous research has repeatedly demonstrated that the tempo and type of music (e.g., the semantic associations that certain pieces or styles of music have with particular countries or regions; e.g., North & Hargreaves, 2008; Spence & Shankar,

2010; see also Section 1.4.2) can influence everything from what we choose to eat and drink, how much we are willing to pay for it, and even what it tastes like, this is the first study to demonstrate such crossmodal effects based on the crossmodal associations between the pitch and timbre of a soundtrack and the taste (bitter vs. sweet) of a real foodstuff. In future research, it would be interesting to extend these results to other tastes, not to mention more complex and competing flavours.

5.3 Experiment 5.2

5.3.1 Methods

5.3.1.1 Participants

13 participants took part in Experiment 5.2 (9 females, aged 18-38 years). The experiment was approved by the Central University Research Ethics Committee of Oxford University. Participants gave their informed consent, reported no cold or other impairment of their sense of smell, and no hearing impairment. The experiment lasted for approximately 60 min.

5.3.1.2 Stimuli

Two odorants were used in Experiment 5.2: coffee and lemon (QL12161 and QL80457, provided by Givaudan, UK). Both odorants were used at three different concentrations: 10%, 20%, or 50% dilutions in dipropylene glycol (Sigma Aldrich). A custom-built computer-controlled olfactometer was used to deliver the odorants. The olfactometer allowed for the delivery of odorized and odourless air at a flow rate of 8 l/min.

Three different sounds were used in Experiment 5.2: a “low” tone consisting of a C2 (64.4 Hz) played by a trombone, a “high” tone consisting of a C6 (1046.5 Hz) played by a trumpet (both from the same database as in previous experiments, http://theremin.music.uiowa.edu/MIS.html, downloaded on 31/10/09), and white noise. All sounds were edited to last for 2 s and were presented over closed-ear headphones (Beyerdynamic DT 531) at a loudness of 70 dB.

5.3.1.3 Procedure

The participants sat on a comfortable chair, 50 cm from the computer monitor. They were instructed to rest their head on a chinrest to which a nosepiece was attached. Breathing instructions were given on-screen. An odour and a sound were presented simultaneously for 2 s (see Figure 5.2 for a schema of the timeline of a trial). The participants were then asked to rate the intensity, the bitterness, or the sourness of the odour on a line scale (50 points) presented on the screen and anchored with *very low* and *very high*. The participants were free to choose when to start the next trial by pressing a key.

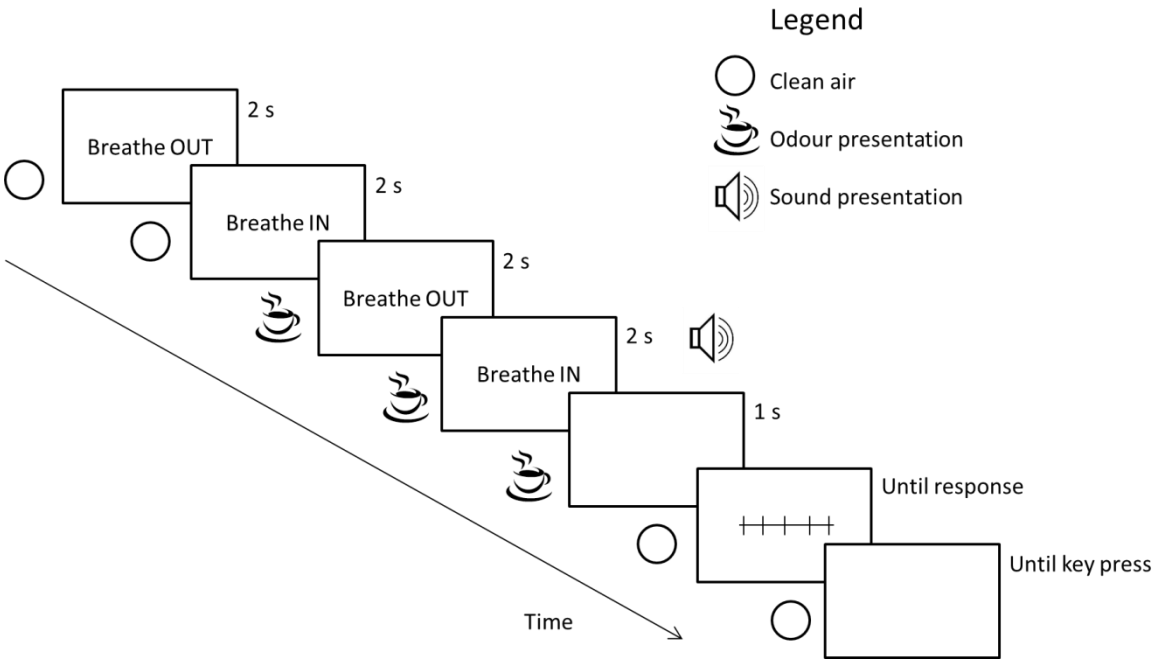


Figure 5.2: Timeline for one trial of Experiment 5.2.

The participants first completed a block of six trials for practice, in which they were presented with both odours at the medium concentration, each combined with the three sounds. In this practice block, the participants rated the intensity of the odours. They then completed six blocks of 36 trials. In each block, they were presented twice with each odour, at each concentration, and with each sound (2x3x3) in a random order. Each of the ratings (intensity, bitterness, and sourness) was used in two blocks. The blocks were presented in a random order.

5.3.2 Results

Three-way repeated measures ANOVAs were conducted in order to assess the effect of the sounds, the odours, and the concentrations on the intensity, bitterness, and sourness ratings. Results showed that the sound played simultaneously with the odour presentation affected the intensity ratings, $F(2,24) = 3.35$, $p = .052$. The high note led to higher ratings (M = 20.44) than the low note (M = 19.23). The white noise induced the lowest ratings (M = 18.11, see Figure 5.3). There was also a main effect of the odour on bitterness ratings, $F(1,12) = 6.19$, p = .029, with the coffee odour rated as more bitter (M = 22.34) than the lemon odour (M = 14.04). For sourness ratings, the effect did not reach statistical significance $F(1,12) = 3.29$, p = .095, but the lemon odour was rated as sourer (M = 24.22) than the coffee odour (M = 17.74). The concentration of the odours had a main effect on all three ratings (intensity, bitterness, and sourness), $F(2,24) = 15.85$, $p < .001$, $F(2,24) = 7.58$, $p = .003$, $F(2,24) = 3.66$, $p = .033$, respectively. The only significant interaction between factors was that between the odours and concentration, which influenced the bitterness ratings, $F(2,24) = 3.66$, $p = .041$.

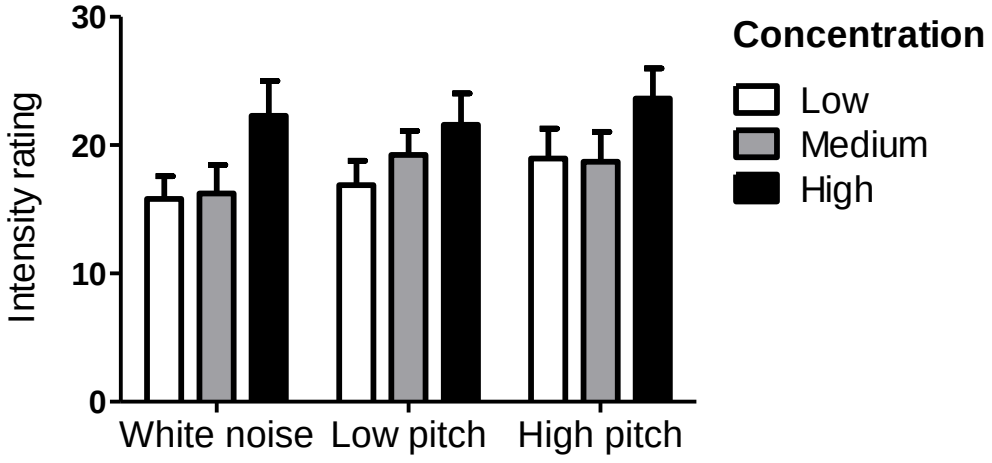


Figure 5.3: Intensity ratings of the odours in Experiment 5.2 as a function of the sound presented simultaneously and the concentration of the odours. Error bars show the SEM.

5.3.3 Discussion

The results demonstrated that sounds can affect the perception of chemosensory stimuli. However, in this experiment, the sounds influenced the intensity ratings, but failed to impact on more specific ratings, such as bitterness and sourness. They also did not affect the two odours used differently, and thus the effect reported here is unlikely to be based on crossmodal associations between basic tastes and pitch. This effect is comparable to that reported by Woods et al. (2011) for taste. The results however suggest that the reducing of intensity induced by noise does not solely depend on the intensity of the sound, as musical notes did not have the same effect. This is in accordance with Seo et al.'s (2011) results showing that verbal and non-verbal noise impaired performance in an odour discrimination task, while music did not.

As mentioned in the introduction (Section 5.1), this experiment was a preliminary study designed to open up new directions for future research. As such, it would benefit from a number of improvements. The bitterness and sourness ratings were chosen in accordance with the first crossmodal associations reported in Experiment 2.1 and reliably found throughout other experiments: Sourness is associated with high pitch, while bitterness is associated with low pitch. However, bitterness and sourness are often confused in naive participants (Hettinger et al., 1999; Meiselman & Dzendolet, 1967; O'Mahony et al., 1979; Robinson, 1970). Training participants might thus be required to obtain reliable results when rating bitterness and sourness. Another issue is the use of taste adjectives to describe odours. Although taste adjectives are readily used to describe odours, their use reflects an association based on previous pairings of the odour with the taste sensation (Prescott, Johnstone, & Francis, 2004; Stevenson et al., 1995). Since these pairings might vary among participants, it might be more appropriate to use descriptors for odours, such as fruity and woody, that have also been demonstrated to correlate with pitch choice.

In the present experiment, odours were chosen that clearly corresponded to the descriptors used (coffee for bitter and lemon for sour), although the results revealed that this was not as clearly reflected in the participants' ratings as might have been expected. Another approach would be to use ambiguous stimuli, which correspond to some extent to both descriptors, as was the case in Experiment 5.1. Sounds might have a bigger effect in the case of uncertainty. In terms of a Bayesian approach, a higher uncertainty would increase the variance of the probability distribution of the sensory features of the stimulus. The prior would thus have more weight in the decision (see Section 1.1.1).

To conclude, the results of Experiment 5.2 do not provide definitive answers concerning the influence of sounds on odour ratings. However, it is a useful first step and provides ideas for further research on the topic, such as modifying the timing of the auditory stimuli, presenting ambiguous odours, using ratings of specific odour descriptors, or providing references for these descriptors.

5.4 General discussion

The results of Experiment 5.1 demonstrate that the crossmodal congruence of a soundtrack presented with a food item can alter its taste. The results of Experiment 5.2, which examined interactions between odours and sounds, were less convincing. While there was an effect of the sounds presented with odours on the ratings of odour intensity, no effect was found on more specific ratings, namely bitterness and sourness. Experiment 5.1 and 5.2 differed in several important ways, which could be the cause for these seemingly contradicting results.

The most obvious difference is in the chemosensory stimuli used. In Experiment 5.1, food items (cinder toffee) were used, so the stimulus consisted of a complex flavour combining taste with retronasal odours. In Experiment 5.2, odours were presented orthonasally. Both flavours and odours have been shown to elicit strong crossmodal associations, but one cannot exclude the possibility that they work through different mechanisms and that sounds thus exert

different impacts when presented simultaneously with flavours or odours. In Experiment 5.2, the participants were required to use taste descriptors to rate odours. As already discussed, this requires participants to associate odours with tastes and might induce more variability.

The sounds used in the two experiments reported in the present chapter were also very different. In Experiment 5.1, the soundtracks were designed to evoke bitterness and sweetness, while in Experiment 5.2, single musical notes were used. Soundtracks were different in their pitch, but also in their timbre, while the musical notes were both played by brass instruments. It is thus possible that the effect found is due to the difference in timbre between the two soundtracks rather than to the difference in pitch.

In Experiment 5.1, the soundtrack started before the participants tasted the toffee, allowing the participants to form a specific expectation about the taste based on the soundtrack, as hypothesized in Section 5.2.3, whereas in Experiment 5.2, the sound and the odour were presented simultaneously. The null result reported in Experiment 5.2 thus strengthens the hypothesis that expectations are more likely responsible for the effect reported in Experiment 5.1.

The length of stimulus presentation also varied greatly between the two experiments. In Experiment 5.1, the participants were free to taste the toffee at their own pace, while in Experiment 5.2, their rating was based on a short, 2-second presentation of the odour. This difference in duration might also have changed how the auditory stimulus was perceived, from a background in Experiment 5.1, to a signal for the presence of the odour in Experiment 5.2. Integration between sounds and chemosensory stimuli might be modulated by the context.

The pairs of adjectives used to rate the chemosensory stimuli were also different. Both the bitter-sweet (Experiment 5.1) and bitter-sour (Experiment 5.2) continua have been shown to be matched to pitch. However, the bitter-sweet continuum also implies a difference in pleasantness, which is not as clearly present in the bitter-sour continuum. However, the

soundtrack did not affect the pleasantness ratings in Experiment 5.1. It is thus unlikely that differences in pleasantness are a necessary component of the effect found in Experiment 5.1.

Finally, in Experiment 5.1, ambiguous stimuli were used, which tasted both bitter and sweet. Moreover, the participants made a single rating on a bitter-sweet continuum. Conversely, in Experiment 5.2, two separate odours were used, and bitterness and sourness were rated separately. The small effect that sound might have on taste perception might only be detected when such ambiguity is present. Following maximum likelihood estimation (MLE) theory, sounds might only be used to disambiguate a situation, while being ignored when the chemosensory stimuli are unambiguous (e.g., Ernst & Bülthoff, 2004).

Given the number of differences between Experiments 5.1 and 5.2, further research will clearly be needed to study these various factors and determine in which conditions sounds affect chemosensory perception.

6 Chapter 6: General discussion

6.1 Key findings

6.1.1 Characterisation of chemosensory-auditory crossmodal associations

The first goal of the experiments reported in this thesis was to try and demonstrate the existence and to characterize crossmodal associations between musical notes and chemosensory stimuli (tastes, flavours, and odours). The experiments reported in Chapter 2 (Experiments 2.1 and 2.2) revealed that sweet and sour tastes (evoked by the names of drinks and food items) were preferentially associated with high-pitched notes, while there was some weaker evidence for an association between bitterness and low pitch. These results were confirmed for real taste solutions in Experiment 3.1. The results of this experiment also extended to flavoured solutions. It also introduced a second musical parameter, timbre, by using notes played by different classes of musical instruments. The method developed in Experiment 3.1 was then used to explore a variety of other stimuli: flavoured milk solutions (Experiment 3.2), crisps (Experiment 3.3), and wine-related odours (Experiment 3.3). All of these types of stimuli were consistently matched across participants to pitch. Fruity flavours and odours were preferentially associated with high-pitched notes, which was to be expected since fruits are both sour and sweet. The choice of the type of instruments seemed to rely less on taste or odour qualities and more on the pleasantness of the stimuli (see Section 6.1.2 below).

6.1.2 Mechanisms of chemosensory-auditory crossmodal associations

The second goal of the experiments reported in this thesis was to examine potential underlying factors that could explain the crossmodal associations observed. Two such factors were studied: familiarity (Experiment 4.1), and pleasantness (Experiment 4.2). Familiarity did not play a significant role in the crossmodal associations between odours and musical notes examined in Experiment 4.1. Pleasantness, on the other hand, was shown to be an essential

factor in the musical instruments associated with the flavours of different types of chocolates in Experiment 4.2, confirming the results obtained in the experiments reported in Chapter 3. The choice of pitch matched to tastes, flavours, or odours remains largely unexplained by these two factors. The associations between pitch and several other perceptual dimensions were surveyed in Experiment 4.3. The results revealed a strong agreement among participants to associate creaminess with low pitch, and crunchiness with high pitch. The textural aspects of food should thus be taken into account in future research on crossmodal associations between pitch and food items. However, texture cannot explain the associations found with odours (Experiments 3.4 and 4.1), nor can it explain the effects with tastes and flavours presented in solutions (Experiments 3.1 and 3.2).

6.1.3 Influence of auditory stimuli on chemosensory perception

The third goal of the experiments reported in the present thesis was to assess the influence auditory stimuli might have on chemosensory perception depending on the congruency of the stimuli presented simultaneously. Experiment 5.1 demonstrated that soundtracks designed to be congruent with either a bitter or a sweet taste, and which were played while participants tasted a piece of cinder toffee, could influence their rating of the stimulus on the bitter-sweet continuum. In Experiment 5.2, musical notes and coffee or lemon odours were presented simultaneously. There was no effect of the musical notes on the bitterness and sourness ratings of the odours (although there was an effect on odour intensity). The experiments conducted to explore this issue are still at a preliminary stage and thus no definitive conclusions can be drawn here. However, it seems that the influence of auditory stimuli on chemosensory stimuli based on crossmodal congruency only happens in specific contexts. Parameters to explore in this regard include the relative onset of the stimuli, the length of the auditory stimuli, as well as the ambiguity and complexity of the chemosensory stimuli involved.

6.2 Theoretical implications

6.2.1 Mechanisms underlying crossmodal associations

Three types of crossmodal associations have been proposed: innate, statistical, and semantically-mediated (Schifferstein & Tanudjaja, 2004; Spence, 2011a; see also Section 1.1.2). There is no reason to think that the crossmodal associations described in the present thesis are innate (although note that it has been suggested that some taste-smell correspondences might be innate, see Shepherd, 2012). Similarly, specific chemosensory stimuli are unlikely to be repeatedly experienced simultaneously with specific musical notes, and thus the crossmodal associations observed are presumably not statistical in origin. The crossmodal associations that have been documented between auditory and chemosensory stimuli most likely belong to the semantically-mediated category. Several models could explain how the matching between stimuli is achieved at a semantic level, through the matching of stimuli on amodal dimensions. For the associations of chemosensory stimuli with musical instruments, a single dimension, pleasantness, seem to be largely responsible for the matching of the stimuli. However, pleasantness was not sufficient to explain the associations between chemosensory stimuli and pitch. Multidimensional models might thus be more appropriate to explain the associations observed. The model proposed by Osgood (Osgood, 1952; Osgood et al., 1957) suggests three main dimensions: hedonic value, potency, and arousal. The hedonic value dimension was consistently found through PCA (Experiment 3.1, 3.2, and 3.4), while a potency (or intensity) dimension was found in Experiment 3.1 and 3.4. The arousal dimension could be assimilated to the complexity dimension found in Experiment 3.2 and 3.4 (see Lévy, MacRae, & Köster, 2006). In order to further explore the explanatory power of Osgood's model for crossmodal sensory associations, one would need to have ratings specifically designed to assess these dimensions for both the chemosensory and auditory stimuli and compare the ratings in both modalities. More recently, another three-dimensional model was proposed to describe the subjective value of an entity, based on the affective (good, pleasant, positive), arousal (diverse, active, powerful),

and cognitive (meaningful, regular, organised) dimensions (Janković, 2010). Alternatively, emotions elicited by stimuli have been suggested to underlie certain crossmodal associations (Collier, 1996; Schifferstein & Tanudjaja, 2004). Two different roles of emotions in crossmodal associations can be hypothesised. First, as it has been suggested that emotions can also be described through a three-dimensional model similar to Osgood's (pleasure, arousal, dominance; Russell & Mehrabian, 1977), emotions could be matched to sensory stimuli in the same way that stimuli can be associated crossmodally (see Figure 6.1a). Second, sensory stimuli could directly elicit emotions, and the matching of emotions elicited by stimuli from different modalities would lead to crossmodal associations (see Figure 6.1b). While in the first case, the amodal space could arguably be considered semantic in nature, the second case, hypothesising a direct matching of emotions, would constitute a new type of crossmodal associations.

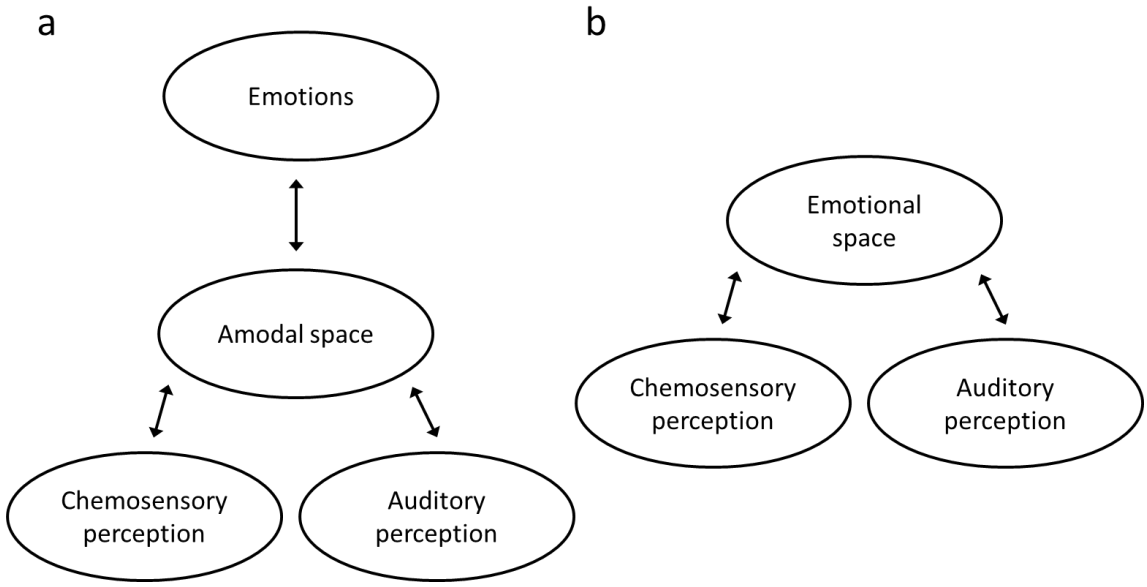


Figure 6.1: Possible role of emotions in mediating crossmodal associations: Associations with sensory stimuli through an amodal space (a), or direct link between sensory stimuli from different modalities (b).

6.2.2 Categorising chemosensory stimuli

The taste adjectives *bitter* and *sour* are often confused by untrained participants, even when these adjectives are used to describe stimuli that are clearly distinguishable (Hettinger et al., 1999; Meiselman & Dzendolet, 1967; O'Mahony et al., 1979; Robinson, 1970). Robinson

suggested that this effect might be caused by the association of bitterness with unpleasantness, so that unpleasantly sour stimuli are then described as bitter. The results presented in this thesis confirm that bitter and sour stimuli can clearly be distinguished, and that they give rise to different conceptual associations, as they are associated with different pitch: Sour stimuli are preferentially associated with high pitch, while low pitch is preferred for bitter stimuli. This matching also underlines the inefficiency of the pleasantness dimension in terms of explaining these crossmodal associations, as both bitter and sour stimuli were rated as unpleasant.

Similarly, the theory of pleasantness as a single dimension in odour discrimination and identification, as suggested by Yeshurun and Sobel (2010), is not supported by the results presented in this thesis. In Experiment 3.4, pleasantness was found alongside two other factors (complexity and intensity) through PCA. This result suggests that more than one dimension may be necessary to represent odour evaluation.

6.2.3 On the absolute versus relative nature of crossmodal associations

One question that has not been investigated in this thesis is whether the crossmodal associations described herein are relative or absolute. For example, is caffeine associated to a specific note, or only to a lower pitch than the other stimuli tested (i.e., in the reference set)? One way to answer this question would be to test the same set of chemosensory stimuli with different ranges of pitches. If the crossmodal associations were relative, the pitch associated with each stimulus would be shifted, whereas if the associations were absolute, the pitch associated with each stimulus would stay the same, or the extreme value would be chosen in the case where the same note was not available in the new range. Given that most people cannot identify the frequency of a note (i.e., they cannot name a note without a point of reference), an absolute association is unlikely. However, the range of frequency that can be perceived by humans is limited. In that sense, an absolute evaluation can be made as to whether a sound is close to one of the extremities, i.e., it is possible to say whether a sound is

high or low-pitch, even without a point of comparison. The associations could thus be relative, but only within a certain range of values.

Ascertaining the type of associations would provide information regarding the possible mechanism(s) underlying the crossmodal associations reported here. Relative associations would point to a matching of stimulus dimensions, where the exact matching depends on the context in which the stimuli happen to be presented. For example, if higher sweetness was matched to higher pitch, as the results presented in previous chapters would seem to indicate, a sweeter stimulus would always be matched to a higher-pitched note than a stimulus lower in sweetness, but the exact pitch would depend both on the range of gustatory stimuli presented, and on the range of pitch provided. Relative associations would also most likely occur at a conceptual level, although adaptation mechanisms at a perceptual level could explain some level of relativity.

The effects crossmodal associations could have on perception would also be different for relative than for absolute associations. If the associations were absolute, hearing a note would lead to an expectation of a specific taste or odour. In such a case, the assimilation-contrast model might be most appropriate (see Section 1.2.6). However, if the associations were relative, then the expectations would depend entirely on the context, and there could be no influence of auditory stimuli on chemosensory perception for a single stimulus out of context. These are the extreme cases, but if the crossmodal associations were relative within a certain range, then the context would make the expectations more precise.

6.2.4 Object-based associations

In comparing crossmodal associations, it is important to differentiate between those applying to features of the same object (e.g., between size and pitch), to those that are not. In many previously-reported cases of crossmodal associations, the associated features originated from the same object, and might thus have been learned through prior experience with objects

in which the two features co-occur. In such cases, expectations would then be based on knowledge (e.g., a red juice is more likely to be tomato juice than orange juice). In the associations reported in this thesis, auditory and chemosensory features did not originate from the same object. It has been shown that features unrelated to an object (e.g., ambient lighting, or shapes presented before the target object) can also affect how it is perceived (Gal et al, 2007). In such cases, the effect is likely due to priming of a concept (e.g., sharpness from shapes), which is then associated with the target in a different sensory modality (e.g., sharpness of cheese, in Gal et al.'s experiment). The results of the experiments reported in Chapter 5 seem to indicate that sounds need to be presented before chemosensory stimuli to have an effect, suggesting that the sounds might have a priming effect. In Experiment 5.1, the high-pitched soundtrack might have primed the concept of sweetness, possibly directing attention to this feature in the toffee that was tasted. Such priming effects probably work through different mechanisms than expectations based on experience, and the assimilation-contrast model might not be appropriate to describe them. More research is clearly needed to determine the extent of such effects and the mechanisms through which they work.

6.3 Practical applications

6.3.1 Marketing

There has been a recent trend to consider all sensory modalities, as well as their interactions, when designing new products and their packaging (Lindström, 2005; Smets, 1995; Spence & Gallace, 2011b). Moreover, the use of synaesthetic metaphors in ads seem to make them more pleasant and novel than literal claims (Nelson & Hitchon, 1999). The results reported here provide some potentially valuable insights into how music could be used in the marketing of a variety of food and beverage products. Given that new food products are most often not tasted before being purchased for the first time, priming associations and inducing the right

expectations in the mind of the consumer through sounds or music, so that the sensory qualities of the product will match the expectations of the consumer, could be particularly fruitful.

6.3.2 Restaurants

Various aspects of the auditory background have been shown to influence patron's behaviour in restaurants (e.g., the volume, tempo, type of music; see Section 1.4.2). The results reported in the research reported in the previous chapters suggest some new parameters of music to explore in this context, namely pitch and timbre. Carefully selecting, or even composing new music, to match (i.e., to be congruent with) the flavours of the dishes served could potentially enhance a patron's experience. The results of Experiment 5.1 demonstrated that sweetness ratings could be increased by presenting an appropriate soundtrack. No effect on pleasantness ratings was found, but more research is certainly needed to reach definite conclusions. Seo and Hummel's (2011) results demonstrating that congruent sounds could increase the intensity and pleasantness ratings of odours are encouraging.

The presentation of congruent sounds has actually already been used in a restaurant setting. The Fat Duck restaurant in Bray (UK) served a seafood dish entitled "Sounds of the Sea", which was presented accompanied by an iPod playing a "sounds of the sea" soundtrack (see Spence, Shankar, & Blumenthal, 2010).

6.3.3 Art

Many artists have been inspired by synaesthesia, or are even synaesthetes themselves (Harrison, 2001). It has been demonstrated that people without synaesthesia presented with audio-visual animations based on the experience of synaesthetes will find them more aesthetically pleasing than random audio-visual pairings (Ward, Moore, Thompson-Lake, Salih, & Beck, 2008). As synaesthetic correspondences seem to share similarities with crossmodal associations (Simner et al., 2005; Ward, Huckstep, & Tsakanikos, 2006), it would be interesting

to investigate whether congruent crossmodal pairings of chemosensory stimuli with musical notes would be preferred over random pairings in an artistic context.

Some artists have already tried to integrate associations between chemosensory senses and audition in their work. For example, the Swiss composer Pascal Desarzens designed an "olfactory concert", with pieces based on eight odours (short description available on http://www.pascaldesarzens.ch/cms/Default.aspx?Page=14452&Menu=281, accessed 04/01/2012).

It is also interesting to note here that following their 2011 study, Mesz, Trevisan, and Sigman are now collaborating with molecular gastronomy Chef Alejandro Digilio on a concert during which canapés designed to be crossmodally congruent with the music will be served (http://www.molecularrecipes.com/molecular-gastronomy/taste-music, accessed 04/01/2012).

6.3.4 Nutrition

Olfactory function can be altered by many factors: age, infections, exposure to toxic chemicals, or neurodegenerative diseases (most notably Parkinson's disease and Alzheimer's disease), to name but a few (see Doty, 2009, for a review). Partial or complete loss of the sense of smell leads to a decrease in the quality of life, and, in particular, less enjoyment of food, which leads to significant alterations of dietary behaviours (Aschenbrenner et al., 2008; Frasnelli & Hummel, 2005; Smeets et al., 2009). Moreover, more than a third of patients with olfactory loss also report changes in the social aspects of food-related behaviours, such as inviting friends for dinner or going out to restaurants (Aschenbrenner et al., 2008). New ways to enhance the flavour of food might thus help people with olfactory dysfunctions. Conversely, reducing the appeal of certain flavours might help dieters resist cravings (Gilbert & Firestein, 2002). A better understanding of crossmodal associations with food and the conditions in which they might influence flavour perception could thus be helpful in terms of improving nutrition, by enhancing or supressing specific flavours through the use of sounds or music.

6.4 Future research

6.4.1 Further dimensions to explore

The neural mechanisms underlying the crossmodal associations that have been demonstrated between chemosensory stimuli and musical notes are still unclear. Based on the results described in the present thesis, a number of dimensions could be further studied. Given the importance of auditory cues in the perception of textural features, such as crunchiness or creaminess, these features might play a role in the formation of crossmodal associations. Moreover, in Experiment 4.3, almost 80% of respondents chose crunchy as a better metaphor for high pitch than creamy. Studying the influence of textural factors might thus help uncover the mechanisms underlying crossmodal associations between chemosensory stimuli and musical notes.

Pleasantness was demonstrated to be an important factor in the matching of musical instruments to flavours and odours. Given the important role of emotions in both chemosensory perception and music processing (see Sections 1.2.7 and 1.3.1), further studies could investigate more complex emotions than the good-bad dimension. For such studies, means of measuring physiological parameters (such as heart rate or skin conductivity; see, e.g., Bensafi et al., 2002) would be useful to have objective measures to complement ratings made by participants. This line of study might further help to clarify the role of emotions in crossmodal associations (see Section 6.2.1).

It could also be interesting to study associations between more than two sensory modalities. Colours have been shown to be associated with certain odours and flavours (Schifferstein & Tanudjaja, 2004; Spence, Levitan, et al., 2010). Moreover, some sound-colour associations are preferred over others (Melara, 1989). Could stimuli be matched in all sensory modalities, i.e., would a colour and a sound that are both associated with a specific odour themselves be associated (see von Hornbostel, 1931)? Answering such questions would help

better understand whether a single mechanism is responsible for crossmodal associations, or whether separate mechanisms are needed to explain associations between different sensory modalities.

Another line of research that could help better understand chemosensory-auditory associations would be to investigate whether new associations can be learned (or existing ones modified) through repeated simultaneous presentations of chemosensory stimuli and musical notes. There is evidence that new odour-taste associations can be learned (Stevenson et al., 1995), and that the expectation that bigger objects are heavier can be modified (Flanagan, Bittner, & Johansson, 2008). Given that it has been hypothesised in this thesis that chemosensory-auditory associations are not the result of statistical learning, one might expect to obtain different results than with odour-taste or size-weight correspondences.

6.4.2 Crossmodal associations in other cultures and through development

Another direction for future research would be to conduct cross-cultural studies (e.g., Walker, 1987). This would help understand the contribution of language and cultural background to crossmodal associations. Affective responses to odours have been shown to vary as a function of culture (Ferdenzi et al., 2011). It would thus not be surprising to find differences in the way chemosensory and auditory stimuli are associated.

Another way to investigate the origins of chemosensory-auditory crossmodal associations would be to study their developmental trajectory. It has been suggested that the use of some categories of metaphors (some based on crossmodal associations) might appear very early in development (see Seitz, 2005, for a review). It might be fruitful to compare the evolution through development of the crossmodal associations reported in this thesis with other crossmodal associations, as well as with metaphors.

6.4.3 Crossmodal associations between chemosensory stimuli and music

The experiments reported in this thesis focused on associations between chemosensory stimuli and single musical notes varying in pitch and timbre. Further research could therefore use the methodology developed here to study more complex musical stimuli, for example musical chords, short rhythm sequences or melodies. The factors measured by Mesz et al. (2011) in the improvisations on taste names made by musicians could also be studied separately (articulation, loudness, duration, and dissonance). One could also modify acoustic parameters of these improvisations, such as pitch or timbre, and study the effect it would have on the associations made by listeners.

The synaesthete E.S., who experiences tastes and flavours in response to musical interval, reports using her synaesthetic perception in order to identify musical intervals (Beeli et al., 2005). It could be of interest to study whether existing or learned crossmodal associations between musical intervals and tastes or flavours might improve the learning of musical intervals in non-synaesthetes.

6.5 Conclusions

Food is a vital, physical necessity. Music might not seem as essential, but it is nonetheless present in some form in virtually every culture (Titon et al., 2009). Both can elicit strong affective reactions. It might thus not be as surprising as it may at first seem that there exist associations between them. The present thesis has described such associations between chemosensory stimuli and low level musical parameters: pitch and timbre. Pleasantness has been shown to be an important, but not sufficient factor to explain the crossmodal associations. Further research along the lines suggested in the preceding section will hopefully give a more complete picture of the crossmodal associations between chemosensory and auditory stimuli, their mechanisms, and the influence they might have on perception when stimuli are presented simultaneously.

7 References

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