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The impact of perceptual interactions on perceived flavor

Jeannine Delwiche

Department of Food Science and Technology, The Ohio State University, 2015 Fyffe Road, Columbus, OH 43210, USA

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Abstract

When eating or drinking, the individual experiences a multitude of sensations, including taste, smell, touch, temperature, sight, sound, and sometimes pain/irritation. This multi-faceted sensory experience is the underpinning of perceived flavor, although certainly some sensations contribute more than others. This paper reviews how all these sensations interact, both on a perceptual and a physical level, and discusses the resulting impact each has on flavor ratings. Interactions between taste and smell, and interactions of the remaining sensations will be discussed. Finally, practical implications of these interactions for sensory evaluation are discussed.

Keywords: Flavor; Taste; Smell; Sensory interaction; Physical interactions

1. Introduction

For many years, scientists have attempted to define flavor. In 1958, Beidler defined flavor in the following way:

> Flavor is the sensation realized when a food or beverage is placed into the oral cavity. It is primarily dependent upon the reactions of the taste and olfactory receptors to the chemical stimulus. However, some flavors also involve tactile, temperature, and pain receptors.

Similarly, the ISO defines flavor as follows:

> Complex combination of the olfactory, gustatory and trigeminal sensations perceived during tasting. The flavour may be influenced by tactile, thermal, painful and/or kinaesthesic effects. (ISO 5492, 1992)

However, neither of these definitions captures the multi-faceted combination of sensations experienced by an individual when eating or drinking, or even smoking, chewing gum, etc. and it is the gestalt (or whole) of this overall experience that is of interest to those eating, drinking, and cooking, as well as food product developers. This paper will review studies that look at the impact of different modal cues on the perception of taste, smell and flavor, as well as the impact of certain physical interactions on these perceptions.

2. Taste and smell interactions

There are many indications that the sensations of taste and smell interact. The most definitive evidence to date of this interaction is that when a subject is presented with a subthreshold concentration of an odor compound (i.e., benzaldehyde—a cherry/almond aroma) in conjunction with a subthreshold concentration of a taste compound (i.e., sodium saccharin—a sweet taste), subjects are able to detect the combination (Dalton, Doolittle, Nagata, & Breslin 2000). This cross-modal summation of subthreshold concentrations of selected compounds demonstrates that central neural integration of taste and smell inputs is occurring. However, integration between benzaldehyde and monosodium glutamate (sometimes described as a savory or brothy taste) does not occur, suggesting that experience with the paired taste and odor stimuli is necessary for integration to occur (Breslin, Doolittle, & Dalton, 2001).

Other studies have shown that overall intensity ratings of taste and smell compound mixtures tend to be slightly less than the added intensities of the unmixed components (Garcia-Medina, 1981; Gillan, 1983; Murphy & Cain, 1980; Murphy, Cain, & Bartoshuk, 1977), although suppression within a particular modality

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E-mail address: delwiche.1@osu.edu (J. Delwiche).

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is greater than that found between modalities (Gillan, 1983). Odor judgments increase as taste compound concentration is increased, and taste judgments increase as odor compound concentration is increased (Bonnans & Noble, 1993; Frank, Ducheny, & Mize, 1989; Murphy & Cain, 1980; Murphy et al., 1977; Philipsen, Clydesdale, Griffin, & Stern 1995). This increase in odor and taste intensity ratings is stronger for harmonious taste–odor pairs, or taste–odor pairs that are typically encountered together (Frank & Byram, 1988; Kuo, Pangborn, & Noble, 1993; Schifferstein & Verlegh, 1996).

This type of taste–odor interaction can result in complicated changes in perceived flavor when complex stimuli are used. When sucrose was added to fruit juices, not only were perceived levels of bitterness and sourness reduced while perceived sweetness increased, but 'vinegar' and 'green' ratings decreased while 'fruity,' 'berry-like,' 'fragrant,' and 'sweet odor' ratings increased (von Sydow, Moskowitz, Jacobs, & Meiselman, 1974). Dumping effects, or the inflation of an attribute rating due to the absence of an appropriate attribute that would allow a participant to respond to a salient sensation (Clark & Lawless, 1994; Lawless & Clark, 1992), could potentially account for changes in ratings after the addition of sucrose.

However this seems unlikely, as there is there is evidence for associative learning of taste–odor qualities (Stevenson & Prescott 1995; Stevenson, Prescott, & Boakes, 1999). Furthermore, the strategy one uses when considering a taste–odor pair, either a synthetic approach focusing on the gestalt (that typically employed by consumers when eating) or an analytic approach focusing on its components, impacts how strongly the taste and odor will influence one another in ratings of taste or smell intensity (Bingham, Birch, de Graaf, Behan, & Perring, 1990; Frank, van der Klaauw, & Schifferstein, 1993; Lawless & Schlegel, 1984; Prescott, 1999, 2001; van der Klaauw & Frank, 1996). This means that the amount of taste and smell interaction that occurs is influenced by the instructions given to the judges, and the strategies these instructions invoke (Prescott, 1999, 2001). Evidence also suggests that the number and type of response alternatives set a context that influences a judge's approach to an evaluation task prior to the presentation of the stimuli (Frank, 2003).

In agreement with the psychophysical data, there is neuroimaging evidence of taste and smell integration. Using PET (positron emissions tomography) scans, Small, Jones-Gotman, Zatorre, Petrides, and Evans (1997) found that the combined activity (measured by cerebral blood flow) evoked by the presentation of taste and smell alone was greater (in the insula, which is the ingestive cortex, and the orbitofrontal cortex, which is associated with emotional decision making) than the activity evoked when taste and smell were presented simultaneously. However, a more recent study using event-related fMRI (functional magnetic resonance imaging) indicates that there is increased blood oxygen level demand (in the orbitofrontal cortex and the amygdala, which is associated with fear) when taste and smell are presented in combination, over and above the summed activity of taste and smell presented alone (Small & Jones-Gotman, 2001). This discrepancy seems to be due to the fact that in the first study, odors were presented orthonasally (on Q-tip swabs held under the nose), while in the second study odors were presented retronasally (in solution). Previous psychophysical research has indicated that an odor that is presented orthonasal is not as identifiable when presented retronasally (Rozin, 1982). These findings are suggestive, and perhaps indicate that when taste and smell compounds are presented together in solution, something more than the sum of its perceptual parts emerges.

Theoretically, when either the taste or odor compound of a highly familiar odor–taste pair is presented in isolation, it may elicit weak ratings of the missing component. This could arise because either taste or smell could weakly stimulate a neuron that responds optimally to their combination. Prescott (2001) has shown that taste–odor pairs can be learned from as little as a single co-exposure. If learning is required to form an odor–taste association, it is possible that the association of a taste–odor pair also could be extinguished. Perhaps with repeated presentation of either component in isolation, and no subsequent paring of the taste and smell, the "enhancement" of ratings would diminish over time.

It should be noted that there are some compounds that elicit both taste and smell ratings. Some compounds that are thought of as taste compounds (e.g. sodium acetate) also have a smell when presented in a vaporized solution (unpublished observation, Breslin laboratory, 1997). Similarly, some volatile compounds have a taste. Most compounds elicit a much stronger response in a particular system, but the possibility that a particular compound may stimulate both taste and smell systems should not be ignored. For example, it has been suggested that the metallic sensation may be a combination of both taste and retronasal smell (Lawless, Schlake, & Smythe, 2003).

Taken together, both psychophysical and neuroimaging findings provide evidence which suggests that taste and smell may be necessary and sufficient stimuli for the perception of flavor, and that if there is a taste–odor association, an odor alone may be sufficient to elicit flavor perception (although a taste alone does not seem to do this). This suggests that there may be something unique about the integration of these sensations which gives rise to a new sensation—flavor.

3. Influence of irritation

The perception of irritants is mediated not by taste and smell fibers, but by other chemosensitive fibers. The perceptual characteristics of chemical irritation, or chemesthesis, are mediated by nonspecific, multimodal somatosensory fibers and are a property of the skin (Green & Lawless, 1991). This raises the question as to whether or not different kinds of chemical irritation can be distinguished, but the definitive work to answer this question has yet to be done.

Studies have shown that some compounds typically thought of as being purely gustatory stimuli, such as salt (NaCl), citric acid, and quinine, show irritant qualities at moderate and high concentrations (Dessirier, O'Mahony, Iodi-Carstens, Yao, & Carstens, 2001; Gilmore & Green, 1993; Green & Gelhard, 1989; McCutcheon & Tennissen, 1989; Prescott, Allen, & Stephens, 1993; Stevens & Lawless, 1986). Similarly, some compounds which are perceived as being purely olfactory (e.g. butyl acetate, a fruity odor) can elicit activity in the trigeminal nerve (which is associated with the perception of irritation), without creating sensations of burning or stinging (Cain, 1974). Considerable electrophysiological and psychophysical evidence indicates that odors at concentrations lower than those generally considered to be non-irritating can stimulate both olfactory and trigeminal chemoreceptors, and this stimulation can contribute to the perceived odor intensity (Maruniak, 1988).

However, it is possible to tease apart chemesthesis and gustation/olfaction. On successive presentations, taste and odor compounds elicit adaptation while irritants give rise to sensitization, or increasing irritation (Cain, 1976; Cometto-Muñiz & Cain, 1984; Green, 1989; Green & Lawless, 1991; Lawless & Stevens, 1989). In addition, irritants have slower onset than do taste and smell compounds (Cain, 1981; Green, 1988; Green & Lawless, 1991; Lawless, 1984; Lawless & Stevens, 1989). These differences between the gustatory/olfactory and chemesthetic components can even be distinguished within a given compound (Green & Lawless, 1991; Prescott et al., 1993). For example, with repeated presentations of high concentration sodium chloride solutions, irritation increases while taste intensity remains constant (Green & Gelhard, 1989). Furthermore, capsaicin desensitization reduces both the irritation and taste of sodium chloride and citric acid, suggesting that part of their perceived intensity is mediated by capsaicin-sensitive fibers (Gilmore & Green, 1993).

When capsaicin is presented in a mixture, it does not alter the perceived taste of sodium chloride, citric acid, or chicken broth (Cowart, 1987a, 1987b; Prescott et al., 1993; Prescott & Stevenson, 1995), although it does reduce perceived sweetness of sucrose and tomato soup (Prescott et al., 1993; Prescott & Stevenson, 1995). In contrast, ratings of capsaicin burn were unaffected by sucrose and were raised by sodium chloride (Prescott et al., 1993); possibly the increased irritation found with sodium chloride is due to its irritative component. The origin of this interaction could reflect cognitive interaction or interactions at the receptor level but the work to answer this question has yet to be done.

Similarly, not only do irritants inhibit the perception of odors, but also odor compounds have been shown to inhibit irritation—although the former inhibition tends to be stronger (Cain & Murphy, 1980). For some odor compounds, perceived irritation increases with increasing concentration (Cain, 1976; Green & Lawless, 1991; Katz & Talbert, 1930), which can lead to a shift in qualitative response profiles whereby compounds are judged as having less odor and more pungency as the concentration increases (Green & Lawless, 1991).

Thus, irritants do interact with the perception of both tastes and smells, inhibiting their perceived intensity. In addition, some taste and odor compounds contain an irritative component, and this component can add to the perceived intensity of a compound without being perceived as either burning or stinging. However, irritation is not a required component for the perception of taste and smell.

4. Influence of temperature

The rules of physical chemistry indicate that there will be an increase in volatile components being released from a sample as it is heated (Atkins & Locke, 2002). It is thought that as a result, odors become more intense as a given sample is heated (Herrmann & Abd-El-Salam, 1981; Herrmann & Poeschel, 1973; Voirol & Daget, 1989). A possible consequence of such a phenomenon would be that a sample might contain volatile compounds that are below threshold levels at lower temperatures, but that are detectable as the sample is warmed.

Given this phenomenon, it is not surprising that Voirol & Daget (1989) found sample temperature (20, 40 and 60 °C) influenced orthonasal ratings of beef-type flavoring, but not retronasal ratings. Similarly, other studies on odor–temperature interactions in sweetened fruit beverages failed to find a temperature influence when aroma was presented retronasally (Cliff & Noble, 1990; Noble, Matysiak, & Bonnans, 1991). These findings, while seemingly contradictory to physical and chemical properties, could be accounted for by the fact that once a liquid is placed in the mouth, it is rapidly brought to body temperature. Thus, temperature differences in such stimuli would be rapidly nullified, making differences in odor intensity fleeting. In contrast to these findings, studies have shown that flavor ratings increase with temperature for beef steaks (Caporaso, Cortavarria, & Mandigo, 1978; Olson, Caporaso, & Mandigo, 1980). This is possibly due to the less rapid change in temperature of solids that would occur in the mouth.

When one considers taste–temperature interactions, although research on taste–temperature interactions has been conducted for more than a century, the findings are ambiguous (Green & Frankmann, 1987; Pangborn, Chrisp, & Bertolero, 1970; Schiffman et al., 2000). There is general agreement among studies that cooling or heating taste solutions above or below ~30 °C tends to raise detection thresholds and alters suprathreshold taste sensations, but there is little agreement about either the magnitude of the effects or the temperatures at which they occur. The variation in findings is large because from one study to the next vast differences exist in the psychophysical methods, stimulus delivery, and temperature control. In addition, most experiments included only one or two taste stimuli (Green & Frankmann, 1987).

A possible explanation for the inconsistencies in the literature was that the temperature of the tongue had not been controlled during testing. Reducing tongue temperature, more so than reducing solution temperature, was demonstrated to be the critical factor for reducing perceived intensity of caffeine and sucrose, although the temperature of neither greatly impacted the perceived intensity of citric acid or sodium chloride (Frankmann & Green, 1987; Green & Frankmann, 1987). Interestingly, the impact of tongue and solution temperature on different sweeteners (glucose, fructose, aspartame, and saccharin) was not the same, indicating that the impact of temperature varied depending upon the compound, not just the taste quality (Green & Frankmann, 1988).

Recent work by Cruz and Green (2000) has indicated that temperature itself can elicit the perception of taste. By placing thermocouples on various regions of the tongue to monitor temperature changes, and by raising or lowering the temperature of the tongue with a Peltier-effect device, the researchers were able to elicit sensations of sweet, sour, salty, and bitter (Cruz & Green, 2000). However, this effect was not found with all subjects, nor were the researchers able to produce all taste sensations on all parts of the tongue. The authors suggested that cooling and heating are triggering taste receptor depolarization, stating that warming could initiate G-protein-coupled receptor cascades (which are associated with sweet and bitter compounds), while cooling could gate Na^+ and H^+ ion channels (which are associated with salts and acids). Such effects would result in taste receptor depolarization, and thus give rise to taste sensations. This is similar to the way one can elicit the perception of lights by pressing against one's eye. What is perceived is visual, although the stimulus is mechanical. This does not mean that pressure contributes to visual perception; it simply indicates that an inappropriate stimulus can elicit a weak response from a sensory receptor by triggering cascade reactions within the receptor through alternate means. These effects of temperature on the receptors would not only account for the phenomenon of thermal taste, but it would also account for the impact of tongue temperature (Frankmann & Green, 1987; Green & Frankmann, 1987, 1988). In addition, it would account for temperature-sensitive neurons that have been found in the human chorda tympani, which is a nerve associated with transmitting neural signals of taste from the front of the anterior tongue (Oakley, 1985). However, the complicated pattern of responses found not only across individuals, but also across regions of the tongue, as various portions of the tongue were alternatively warmed and cooled suggest that things may be even more complicated than warming initiating G-protein-coupled receptor cascades and cooling gating Na^+ and H^+ ion channels.

In sum, temperature has an impact on the perception of taste, smell and flavor, possibly through the triggering of cascade reactions in receptors (by suboptimal stimuli) in the case of taste mechanisms, and through some yet to be elucidated mechanism in odor.

5. Influence of color

Although there are many different features to a food item's visual appearance, only the impact of color has received much attention. Several studies have shown that color greatly impacts the ability of subjects to identify food and beverages, with uncolored and miscolored items being identified correctly less frequently than appropriately colored items. This effect has been found with table jellies (Moir, 1936), sherbet (Hall, 1958), wine gums (Teerling, 1992), and noncarbonated, fruit-flavored beverages (DuBose, Cardello, & Maller, 1980; Philipsen et al., 1995; Stillman, 1993). Similarly, odor identification is lessened when odors are presented without color cues or when they are paired with inappropriate colors (Blackwell, 1995; Davis, 1981; Zellner, Bartoli, & Eckard 1991). Taken as a whole, these results indicate that individuals associate certain flavors (and odors) with specific colors and when the colors are altered, the flavor/odor identification is decreased: the stronger the color–flavor/odor association, the greater the impact of color.

While the impact of a particular color (e.g. red, green, yellow, colorless) on a given taste has been inconsistent across studies as shown in Table 1 (Frank et al., 1989; Maga, 1974; Pangborn, 1960; Pangborn, Berg, & Hansen, 1963; Pangborn & Hansen, 1963), compelling evidence indicates that learned color–taste associations impact perceived taste, even in complex stimuli such as wine (Pangborn et al., 1963). Similarly, Roth, Radle, Gifford, & Clydesdale (1988) altered the relationship of green and yellow colors in lemon and lime flavored sucrose solutions and found that these color changes had an impact on sweetness ratings. In contrast to taste–odor pairings, for color-odor pairings Zellner and

Table 1
Summary of the impact of color on perceived taste

Author(s)	Stimuli	Colors	Attribute	Outcome	Method
Pangborn (1960)	Aqueous sucrose solution	Red Green Yellow Uncolored	Sweet	No effect	2-AFC
	Pear Nectar	Red Green Yellow Uncolored		No effect Less sweet No effect Sweeter	
Pangborn and Hansen (1963)	Pear Nectar	Red Green Yellow	Sweet	No effect	Ratings
		Blue Uncolored	Sour	No effect	
Pangborn et al. (1963)	Wine—Naïve drinkers	Rosé Sauterne Sherry Burgundy	Sweet	No effect	Ratings
	Wine—Experienced drinkers	Claret		Rosé sweetest; Claret least sweet	
Maga (1974)	Aqueous solutions of sodium chloride, sucrose, citric acid, and caffeine	Red Green Yellow Uncolored	Salt	No effect No effect No effect No effect	Recognition Threshold
		Red Green Yellow Uncolored	Sweet	No effect Lowered Raised No effect	
		Red Green Yellow Uncolored	Sour	No effect Lowered Lowered No effect	
		Red Green Yellow Uncolored	Bitter	Raised No effect No effect No effect	
Frank et al. (1989)	Aqueous sucrose solution	Orange-red	Sweet	No effect	Ratings

Kautz (1990) found that solutions were rated as having more intense odors with color cues than without, regardless of color-odor appropriateness. However, Morrot, Brochet, & Dubourdieu (2001) found that when white wine was colored red, individuals tended to describe the wine with more red wine odor terms (which tended to describe red or dark objects) instead of using white wine odor terms (which tended to describe yellow or clear objects) as was done with the same wine uncolored.

Finally, a general trend exists in the literature indicating taste and/or flavor intensity increases as the color level increases. This effect has been found with flavored sucrose solutions (DuBose et al., 1980; Johnson, Dzendolet, Damon, Sawyer, & Clydesdale, 1982; Johnson & Clydesdale, 1982; Johnson, Dzendolet, & Clydesdale, 1983), yoghurt (Norton & Johnson, 1987; Teerling, 1992), and cakes (DuBose et al., 1980). It seems likely that some association exists between color intensity and taste/odor/flavor intensities, despite the fact that increasing color does not always impact on intensity ratings (Philipsen et al., 1995). Perhaps a familiarity with beverages made from powders or concentrates, and their tendency to increase in these sensations as color increases, is responsible for this association. Clydesdale (1993) argues "...its [color's] effect seems to result from learned associations rather than from inherent psychophysical characteristics because these effects often do not conform to Steven's power law." However, the elimination of visual input with a blindfold does not significantly alter flavor from that of a colorless solution (Zellner & Kautz, 1990), indicating that while color can alter perceived taste, smell and flavor ratings, the elimination of visual input does not eliminate the perception of flavor.

6. Influence of texture

The nature and amounts of the volatile odor and nonvolatile taste compounds are major determinants of flavor (Overbosch, Afterof, & Haring, 1991). It has been assumed for some time that texture controls the accessibility of these compounds to taste buds and olfactory cells, with that availability at a given time depending upon the breakdown of the food matrix (Crocker, 1945). However, recent research suggests that somatosensory tactile stimuli can interact with taste and aroma, modulating their perception (Baek, Linforth, Blake, & Taylor, 1999; Cook, Hollowood, Linforth, & Taylor, 2003; Hollowood, Linforth, & Taylor, 2002; Weel et al., 2002).

Christensen (1980b) demonstrated that increasing levels of sucrose, citric acid and sodium chloride altered perceived viscosities of solutions. Similarly, increasing the viscosity of a solution has been shown to decrease both taste and flavor intensity (Arabie & Moskowitz, 1971; Baloga, Carr, Guinard, Lawter, Marty, & Squire, 1994; Christensen, 1980a; Kokini, 1985, 1987; Kokini, Bistany, Poole, & Stier, 1982; Marshall & Vaisey, 1972; Moskowitz & Arabie, 1970; Pangborn & Szczesniak, 1974; Pangborn, Trabue, & Szczesniak, 1973; Stone & Oliver, 1966; Vaisey, Brunon, & Cooper, 1969). Even with more natural stimuli (tomato juice, orange drink, and a coffee beverage), increased viscosity still depressed flavor and aroma (Pangborn, Gibbs, & Tassan, 1978).

Increasing the amount of gelling agent in a food will not only give the product a thicker texture, it will also slow the diffusion of components throughout the product and from the product matrix to the taste and olfactory receptors (Overbosch et al., 1991) Altering the proportion of fat in a product changes not only its texture, but also the flavor release of both water-soluble and fat-soluble volatile and non-volatile components, as well as the amount of each released (King, 1994; Kinsella, 1990). However, increasing gel thickness does not significantly alter in vivo measurement of volatile concentration in-nose (Baek et al., 1999; Cook et al., 2003; Hollowood et al., 2002; Weel et al., 2002), despite significant changes in odor and flavor perception. Instrumental insensitivity does not explain the lack of significant difference found for these in vivo measurements since differences can be measured between gels which contain different amounts of odor compound (Weel et al., 2002). Furthermore, evidence does not support the contention that decreases in perceived odor perception are due to decreases in perceived taste, presumably caused by a change in flux of taste molecules across a boundary layer of fluid to the tongue's surface. Diffusion/mass-transfer of non-volatiles alone, as estimated by theoretically derived diffusion coefficients, are not sufficient to explain observed changes in perception (Cook et al., 2003).

Integration of texture, taste, and smell would explain the above findings. Sensory pathways are known to overlap widely in the periphery, with so-called "gustatory nerves" responding to taste, tactile and thermal stimulation, all of which occur simultaneously during ingestion. Neurological evidence indicates the convergence of taste, olfaction and somatosensory inputs (Cerf-Ducastel, Van de Moortele, Macleod, Le Bihan, & Faurion, 2001). The interaction of texture with taste, smell, and flavor has only begun to be revealed by the recent advent of techniques that allow the simultaneous measurement of human perception and physical concentrations in vivo.

7. Influence of sound

Many assert that sound influences the perception of flavor (Dubner, Sessle, & Storey,1978; McBurneym 1986; Zapsalis & Beck, 1985), yet to date no research has been conducted which demonstrates this. The impact of audition on the perception of foods has focused instead on food's textural properties, typically asking subjects to assess crispness (Christensen & Vickers, 1981; Sherman & Deghaidy, 1978; Vickers & Bourne, 1976a, 1976b; Vickers & Christensen, 1981), or crackliness (Vickers, 1984). Studies in which auditory cues were blocked with a masking noise while subjects scored crispness or crackliness by chewing gave very similar ratings to those made when auditory cues were not masked, although it in unclear how successful a masking tone would be at eliminating the transmission of sound via bone conduction (Christensen & Vickers, 1981; Vickers, 1987; Vickers & Wasserman, 1980). Regardless, these studies suggest that auditory cues give largely redundant information about a food's structure, information that is also indicated by kinesthesis and somesthesis. While the definitive research remain to be done, the interaction of sound with the chemical senses seems unlikely.

8. Discussion and practical implications

This paper has considered the interactions of taste, smell, color, texture, sound, irritation and temperature and how these components interact. These demonstrated interactions are summarized in Fig. 1. While most of these sensations have an impact on flavor ratings, there seems to be something unique about the combination of taste and smell. Taste and smell confusions resulting from referral are frequent, almost as if

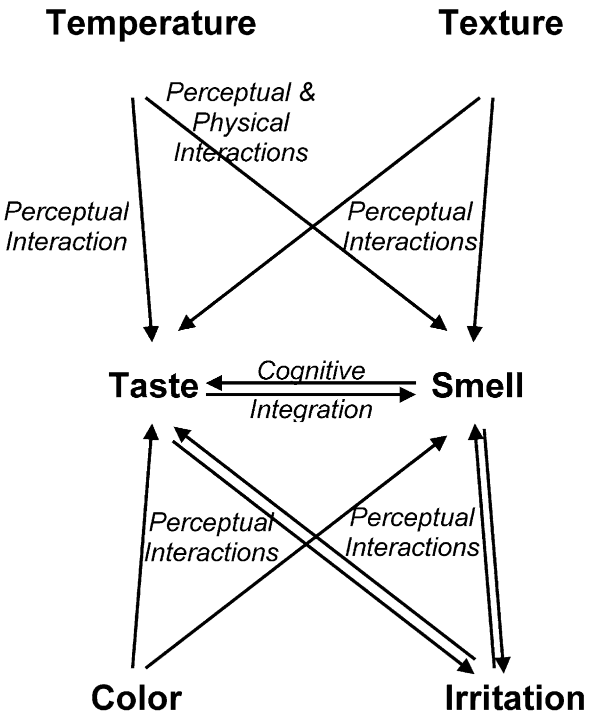

Fig. 1. Summary of perceptual interactions evoked during ingestion. Arrowhead indicates a modality that has been demonstrated to interact with another modality.

the combination of the two is so anticipated that it is difficult to perceive one without perceiving the other. Furthermore, there is no combination of sensory modalities that excludes taste and smell and still creates a flavor. Regardless, color, texture, sound, irritation and temperature have all been definitively demonstrated to influence flavor, either through a perceptual interaction or a physical one.

The practical implications of these physical and perceptual interactions are extensive. One of the most important implications of these interactions is that when one is conducting sensory analysis of a product, one cannot simply ask a panelist to ignore a particular aspect of the product, regardless of amount of training. Each attribute contributes not only to the perception of the attribute itself, but also to the perception of the other attributes present.

Odor and taste interact so profoundly that they can impact the ratings of one another. If one wishes to compare the sensitivity of a panel at detecting differences in sweetener concentration to that of a high-pressure liquid chromatograph, then one should have panelists wear nose clips, thus eliminating any interference from odor. Similarly, if one wishes to compare the discriminability of products with an electronic nose or gas chromatograph to that with a sensory panel, then one should have panelists simply sniff the products without placing them in the mouth. However, if one wishes to know which products will be perceived as tasting sweeter by consumers, then sweetness ratings should be made by panelists with whole-mouth tasting and without nose clips. This is especially important if one is trying to map consumer preference onto the perceived sensory attributes of the product.

The ability of irritants to suppress both tastes and smells also has practical implications. If one is creating mild, medium, and hot salsas, altering only the level of capsaicin is unlikely to result in three acceptable products. The balance of the taste and smell attributes will depend upon the level of irritant included, requiring that each product be optimized separately for each irritation, or capsaicin, level. Furthermore, the phenomenon of sensitization and desensitization to irritants, and of adaptation with taste and smell, very much limits the number of samples a person can reliably assess in a given session. The more subtle the distinctions between products, the fewer that should be sampled each session.

The physical interaction of temperature with odor and the sensory interaction of temperature with taste both lead to one obvious practical conclusion; samples should be evaluated at the temperatures at which they will be used. Panelists' assessment of tomato sauce may miss subtle odor off-flavors if it is presented cold, an obvious disaster for a tomato sauce producer. Similarly, the balance of sweetness, sourness, and fruitiness may appear different for a juice served at room temperature versus at a refrigerated temperature. Attempts at product optimization could be dismal failures if it occurs at the wrong temperature.

For many years, color differences between products have been masked when judges were asked to evaluate product flavors. Given the impact color has on both taste and smell, this practice seems to have some true merit, but only under certain circumstances—it depends upon the goals of the research. If the goal is to correlate panel ratings with instruments, then color masking is an excellent idea. However, if the goal is to see which products consumers prefer, it is not. While some would argue that it is important to know which product is preferred by flavor alone, this information is unlikely to result in an accurate depiction of how products will compare in the marketplace or home (Teerling, 1992).

The tendency for people to mislabel taste, smells, and flavors so that they match colors has implications for term generation in descriptive analysis. Consider the findings of Morrot et al. (2001), where coloring a wine red cause subjects to use a different set of descriptive terms for the aroma. This means that a descriptive panel may describe darker samples as having more caramel, cooked or burnt notes and lighter samples as having more doughy notes. During flavor and taste term generation, it may be beneficial to eliminate visual cues, either by masking lights, opaque covered cups, or blindfolds.

While texture does not seem to interact perceptually with taste and smell, it most certainly has a profound impact on flavor release. Examples of this being ignored were abundant when food companies first began making reduced-fat products. Removing the fat and replacing it with a bulking agent could result in a different proportion of polar and nonpolar fractions, into which taste and smell compounds partitioned themselves. This seemingly simple change resulted in products with a poor balance of taste and smell, as well as altered textures. Similarly, if you give a yogurt or pudding a firmer texture, there will be a lower release of volatiles and thus reduced odor ratings. Thus, it is important to keep in mind that while textural changes may not react 'chemically' with taste and smell compounds, its overall impact can be quite large.

While much research has been done examining the impact of the different senses on the perception of taste, smell, and flavor, there are still unanswered questions and areas that require additional investigation. Except for taste and smell, the impact of associative learning has not been investigated for any of these interactions. Other topics, such as the impact of somatosensory input on taste/smell/flavor and the impact of temperature on taste perception, have only just begun and further research is needed to definitively determine the underlying mechanisms of these interactions.

Perhaps it is not surprising that all of the sensations experienced while eating (or otherwise manipulating a substance in the mouth) are crucial to that experience, nor that many senses interact with one another on a perceptual level. One thing is certain: taste, smell, touch, temperature, sight, sound, and sometimes pain/irritation all have a tremendous impact on whether foods and drinks will be accepted or rejected, and liked or disliked.

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