FLAVORS, OVERVIEW

1. Introduction

Vital to the study of flavor chemistry is an awareness of the relationship of chemical stimuli to the human sensory system it stimulates. Though focus may be on one aspect, neither the stimuli (usually food or beverage) nor the human perceptual system can be evaluated in total isolation of the other. Understanding the relationships between stimulus chemistry and sensory perception requires interdisciplinary collaborations. The specific compounds that activate the chemical senses can be studied with traditional chemistry techniques once their sensory activity has been verified by sensory testing. Furthermore, the behavioral response to flavor cannot be evaluated without the use of chemical stimuli of known composition. It is not necessary to be an expert in physiology, neurobiology, or psychology to study flavor chemistry, but the selective nature of the sensory system must be accounted for in any compositional analysis of food flavor.

1.1. Definition of ''Flavor''. *Flavor* is a term used with a variety of meanings depending on the context. In food science, *Flavor* generally refers to the sensory perception of food or other substances consumed orally, but it is also used to refer to the substance itself that cause flavor perception. A creative flavorist often uses *flavor* to refer to ingredients, eg, flavoring oils and essences, materials added to foods to impart or modulate flavor. There are many other uses for the word flavor from classifying food for marketing purposes, eg, "vanilla" ice cream to the use of *flavor* by physicists to designate elementary particles called quarks. With this broad usage, precise language needs to be employed to clearly communicate about flavor.

1.2. Flavor, the Perception. Flavor perception is a mental experience imparted mainly by the chemical senses of taste, smell, and chemesthesis (chemosensory responses of the trigeminal nerves). Texture, color, and sound also modulate flavor experiences as well as memory, emotion, and context. Furthermore, the variability between people as to what compounds they can detect combined with their differing life experiences cause important differences in how they experience flavor. Flavor perception can be used narrowly to refer to the olfactory response alone or more broadly to include the entire food or beverage experience.

1.3. Flavor, the Chemical Stimuli. Generally, foods contain thousands of chemicals, yet only a small fraction act as stimuli for flavor perception (1). In general, flavor chemicals must: (a) be capable of activating a chemoreceptor; (b) be delivered to the receptors at a concentration above their detection thresholds; and (c) volatilize to activate the brain processes that convert chemosensory input into a conscious percept.

Characterization of a chemical as capable of activating a chemoreceptor can be done objectively. Some individuals may not be able to detect some compounds, but a generalized list of stimuli is attainable. The Flavornet (www.flavornet.org) does just this for aroma compounds, listing only compounds that have been clearly demonstrated to create aroma perception in at least some people. The presence of these detectable compounds in a food is not sufficient criteria for perception. Concentration at the receptor along with many other interactive factors determine whether the compound that is present will contribute to the flavor and how it will contribute. The events of eating or drinking are dynamic processes in which equilibrium is never achieved, thus the concentration of stimuli available to receptors is constantly changing with time and dependant on the mouth environment (2–5).

It has been observed that flavor stimuli are active across a large range of concentrations. The magnitude of difference in activity concentration of compounds inducing taste versus aroma is on the order of 1 million. Table 1 demonstrates the wide range of activity concentration and size for aroma, taste, and chemesthesis (6–8). This article will focus on aroma contribution to flavor, though taste and chemesthesis will be briefly addressed.

2. The Perception of Aroma

Aroma perceptions are the result of interactions between a person and volatile chemical stimuli. Human physiology influences the delivery of the stimuli to the receptors located on the olfactory epithelium. The complexity of the receptor system leads to the capability of tens of thousands of aroma perceptions, while only a limited number of chemicals contribute to aroma. Many factors of physiology, psychology, and genetics contribute to the variability of perception amongst people. Very low concentrations can be detected yet relatively large changes in concentration are necessary for a change to be discernible. Some psychophysical laws give guidance in anticipating select aspects of the perception resulting from the aroma stimuli.

2.1. Anatomy and Physiology. A person may experience aroma sensation from volatiles following two different routes to reach the olfactory receptors: (1) orthonasal smelling occurs when volatiles released enter through the anterior nares on inhalation, and (2) retronasal aroma occurs when volatiles or aerosols released from food in the mouth enter the nasopharynx during exhalation (see Fig. 1). The orthonasal route is followed when something is sniffed through the nostrils to produce smell and is often referred to as fragrance or odor perception. Perception of compounds at the olfactory epithelium is independent of the route taken (9,10).

Extensive efforts have been made to develop techniques to simulate the composition of the volatiles released into the retronasal route. This concept is often referred to as “flavor release”. Flavor release is further discussed in the section on Odor Activity. Conditions in the mouth that may affect flavor release include air flow (breath), mastication (mass transfer), temperature, and saliva (dilution and enzymatic action); with air flow having the greatest impact (11). Therefore, when sampling volatiles from a food, it is important to consider the dynamic conditions of eating. The ratio of volatiles from a closed system at equilibrium may be very different from the volatiles’ ratio under open dynamic conditions. In this nonstagnant system, time profiles further contribute to the experience (12–16).

2.2. Neurology. Olfactory genes represent the largest portion of the human genome specific to one function; accounting for $\sim$3% of human DNA (17,18). With the vastness of the neurological processing of olfaction, it was not until fairly recently that breakthroughs in understanding the system were considered so profound as to warrant the highest international recognition in science: The Nobel Prize in Physiology or Medicine for 2004. The Nobel Prize was awarded to Richard Axel and Linda Buck for clarifying the organization of the olfactory system and identifying olfactory receptors (19). From the active genes, ~400 types of receptors exist, and each cell expresses only one receptor type. Each receptor consists of a chain of amino acids that traverse the cell membrane seven times. The chain creates a binding pocket where the odorant can attach.

The olfactory neurological design is unique from any other of our senses in many ways. Unlike any other receptor cells, olfactory receptor cells are true nerve cells that project directly into the brain and live ~30 days. The receptor cells send signals directly to distinct micro domains or locations, *glomeruli*, in the olfactory bulb. Receptor cells with the same type of receptor send signals to the same glomerulus. These micro domains relay the information to other parts of the brain, where the information from several olfactory receptor types is combined, forming a pattern. This pattern is then processed in combination with memory and other sensory experiences forming the olfactory perception (aroma or fragrance)(20).

Flavors and fragrances are typically composed of multiple odorant molecules, and each type of receptor may be activated by multiple odorants with various intensities (21–24). Further, odorants may activate multiple types of receptors. Variability in genetic coding results in some individuals missing select olfactory receptor types (25–27). These genetic anomolies may result in what is called *specific anosmia* (28–31,6). *Anosmia* is the lack of olfaction, or a complete loss of the sense of smell that may be temporary or permanent. *Specific anosmia* is defined as responses greater than two standard deviations from a population mean or the mean of the most sensitive group in a bimodal distribution (29). The resulting experience for the individual is no detection or suppressed detection of a select odorant(s), while the ability to smell most other compounds is normal.

Consideration of specific anosmia can be integrated into quality control during manufacturing of items where the fragrance or aroma is an important characteristic. If the odor or aroma quality of a product is being evaluated by only one quality control individual, the risk of a malodor being missed due to specific anosmia may be critical. While it may not be practical to utilize a full sensory panel in production quality control, using two individuals for analyses reduces the risk exponentially.

2.3. Psychology. Aroma perception is not processed in isolation from other senses, context, and memory. Sensory stimuli from the other senses contribute to shaping each aroma experience. An individual may have a variety of perceptions to the same stimuli in different contexts, influenced by extended exposure to an odorant and presence of other nonaroma stimuli. Memory has a profound affect on an individual's olfactory cognition, making each person's experience unique.

Interactions With Other Senses. Input from other senses may affect the aroma perception (32). Professor Andy Taylor at the University of Nottingham showed how sweet and mint perception were closely related in a study measuring the concentration of sweetener in the mouth and mint aroma compounds in the breath while chewing gum and the resulting perception (Fig. 2) (33). The mint perception ceased when the sweetener in the mouth was gone, yet the mint aroma chemicals were still fully present. Expected associations with color can lead to effects on aroma perception, eg, a purple sweet fruity beverage may be described as "grape" regardless of the fruit aroma contribution. The aroma intensity of a lighter colored beverage may be perceived as less intense than the same aroma concentration in a darker colored beverage (34–37). Translation of the experience into linguistic expression further complicates measuring aroma perception.

Adaptation. Olfactory adaptation is a common occurrence (33,38–40). When a woman walks down the hall leaving behind an intense plume of fragrance, and you wonder how she is unaware of the overwhelming stench; she has likely experienced adaptation to the fragrance and is unaware of the offense. Adaptation occurs with repeated or prolonged exposure to an odorant leading to stimulus-specific decrease in olfactory sensitivity to that odorant. This state is temporary and the sensitivity recovers over time in the absence of further exposure. The extent and time of adaptation and recovery are dependent on the concentration of the odor and on the duration of exposure. Adaptation may also involve receptor level interaction and saturation. Human neurology is designed to detect changes and as such, attention is paid to changes while constant stimuli receives limited attention, much like awareness of clothing on the skin.

Memory Effect. Even the same odorants at the same concentration can produce different perceptions for the same individual dependent on the context. This is similar to the phenomenon behind optical illusions, eg, the famous young lady−old lady. The same stimuli are provided, but the interpretation varies dependant on focus as to whether an old or young lady is seen (Fig. 3). Odors have a strong link to memory, thus an individual's experiences will influence the aroma perception. The ability of an odor to evoke strong, vivid memories of a past experience is called a Proustian phenomenon, in honor of French writer Marcel Proust who described this experience in relation to madelines in *Remembrance of Things Past*.

2.4. Psychophysics. The ability to predict how aroma compounds contribute to perception is a constant quest in flavor and fragrance research. Some useful psychophysical precepts that describe aroma perception in relationship to quantified stimuli are briefly described below. Detection thresholds are extensively variable between individuals in addition to huge variations for an individual dependent on context. Therefore, these precepts are mostly applicable as guidance in understanding the experience and designing experiments; while the imprecision of thresholds limits their predictive pertinence (40). Relatively large chemical changes are necessary to create a difference in aroma perception. With threshold measurements so variable and a relatively large change needed for a person to perceive a change in odor, very precise measurements of concentration in the food become impractical. Chemical measurement is likely to be much more precise and accurate than the psychophysical values computed. Small chemical changes that modern chemical analyses are capable of detecting (eg, with stable isotopes) are excessively precise and may be misleading because these small changes may impart no change in the aroma perception.

Psychophysical Precepts. *Odor Units or Odor Activity Units.* Odor activity units (OAVs) are ratios of the concentration of an odorant to its detection threshold in the food itself (1). Odor activity units correlate composition with potency. The concept of odor units has been applied with several different names like "aroma value" (41), "unit flavour bases" (42), and "threshold odor number" (43).

$$\text{OAV} = \Phi/\Theta \tag{1}$$

where Φ is the concentration of the odorant (can be measured with error on the magnitude of 0.01%) and Θ is the threshold of the odorant (error on the magnitude of 1000%).

CharmAnalysis or AEDA. CharmAnalysis and Aroma extraction dilution analysis (AEDA) are methods to estimate the potency of each aroma compound in a system based on dilution to threshold or dilution analysis (ie, titer) (1,44–46). Charm values derived from CharmAnalysis are measures of the areas under gas chromatography olfactometry (GCO) peaks that are derived from both the dilution and the duration of odor events, similarly, dilution factors (FD) derived from AEDA are the number of times that a sample can be diluted before an odor disappears from a GCO chromatogram. Under ideal conditions OAVs are proportional to the resulting Charm or FD values.

Steven's Power Law. Stevens' power law describes the relationship between the magnitude of a stimulus and the perceived intensity (47,48). In the case of aroma, the stimulus magnitude is given as concentration at the receptors. Perceived odor intensity has a compressive exponential relationship with concentration.

The general form of the law is

$$\Psi = \mathrm{k}\Phi^{n} \tag{2}$$

where Ψ is the perceived intensity of a stimulant, k is a constant, Θ is the stimulus level, and n is the Steven's law exponent (0.3–0.8 for aroma).

Odor Spectrum Value. Odor spectrum value OSVs are a transformation of potency data, eg, charm values with a Steven's law exponent and normalization to the strongest odorant (1,47,48). They are independent of concentration. The OSVs allow potency data from different experiments as well as different laboratories to be compared.

$$\text{OSV} = (\Phi/\Phi_{\max})^{0.5} \times 100 \tag{3}$$

where Θ is the stimulus level, $\Theta_{\max}$ is the maximum stimulus level within the system, and 0.5 is an approximate Steven's power law value for odor.

Weber Ratio. The Weber ratio describes the amount of stimulus change required to perceive a difference (49–51). The just noticeable difference (jnd) of a sensory perception is proportional to the original stimulus. A typical Weber ratio for olfaction is 30%, in which case a 30% difference in concentration would be necessary for a perceived difference.

$$R = \text{jnd}/s \tag{4}$$

where R is the Weber Ratio, jnd is the just noticeable difference for discrimination (change in odorant concentration required to perceive a difference), and s is the magnitude of the stimulus.

Weber–Fechner Law. The Weber–Fechner law is an extension of the Weber ratio concept with an addendum that just noticeable differences are additive (52–54). The perceived intensity of an odorant is proportional to the logarithm of the odorant concentration.

$$\mathrm{jnd} = \mathrm{A}\log(s) + \mathrm{B} \tag{5}$$

where jnd is the just noticeable difference for (change in odorant concentration required to perceive a difference), s is the magnitude of the stimulus, and A and B are fitted constants.

Potency Versus Intensity. Potency is a measure of the ability of the odorant to affect the olfactory sensors and is a function of concentration (it is an activity). Intensity describes magnitude of sensation and may be described using words like “strong” or “weak”. Odor units, odor activity units, Charm, and FD values refer to potency. Steven’s law and odor spectrum values refer to intensity, while, the Weber ratios and Weber–Fechner law describe discrimination of change. Neither potency nor intensity should be confused with “importance”. Importance of an odorant is relative and reliant on the context and character impact.

3. Chemical Characteristics of Aroma

Aroma compounds, also called odorants, are the ligands of the olfactory system. The dynamic context of the food (the mouth) affects what odorants in the food or beverage will be available to interact with the receptors. Ascertaining the role of odorants in a perception necessitates a complicated process requiring several stages of analyses, outlined in the section In-Depth Determination of Aroma Impact Components of a Food. Several factors including taste interaction, adaptation, suppression, and genetic make up, affect the interpretation of the neurological pattern resulting from the odorant stimuli.

While it is not meaningful to list classes of compounds, eg, esters, acids, alcohols, ketones, etc, that are odorants, there are three prerequisites that characterize aroma compounds: volatile, odor active [capable of activating olfactory receptor(s)], present at a sufficient concentration *in situ* to influence the perception.

Meeting these criteria does not necessary mean that the compound contributes to aroma perception, but these criteria must be met in order to contribute to the aroma. Psychophysical analyses are necessary to further identify if and how a compound contributes to the flavor.

3.1. Volatility. All aroma compounds are volatiles, but not all volatiles are odorants. Aroma is imparted by compounds located at the olfactory epithelium that have followed the pathway through the nasal pharynx from the mouth, referred to as the retronasal route (see Fig. 1). Smell activates the same olfactory receptors in the same way, only they reach the receptors via the orthonasal route. Physical conditions in the mouth like temperature, air flow (breath), mastication, and saliva effect the kinetic and thermodynamic state of the dynamic system influencing the retronasal composition (55,56).

Not all chemicals with potential to volatilize will volatilize from the food or beverage in the context of eating to be able to reach the olfactory receptors. Often a compound that is volatile in its pure form and present at a high concentration in the food system cannot contribute to the aroma perception since it does not sufficiently volatilize out of the food system. Some reasons for inhibition of volatilization include solubility, mass transfer, ionization, and binding complexes with other components. The contribution of vanillin [*121-33-5*], the characteristic vanilla compound, is often over estimated when based on the concentration found in a food since it has a relatively small partition coefficient, ie, only a small fraction of the concentration found in the food volatilizes to actually reach the olfactory epithelium. The volatilization of aroma compounds from food during eating is referred to as flavor release.

Any change in the food composition will effect the partitioning of volatiles from the food into the breath (57,58). Nonaroma constituents of foods, eg, protein, fat, fiber, and carbohydrates, can influence the extent to which a particular compound volatilizes thus affecting the ratio of volatilized compounds and possibly the perceived flavor. Removing the fat or sugar from a product causes the ratio of volatiles released to be very different from the ratio of volatiles released from the original food. The odorants become "unbalanced" in the new system creating the challenge of matching the flavor release from the original system to achieve a similar aroma perception. Different concentrations of the odorants in the food base will be necessary to achieve the same retronasal headspace concentration from which perception is derived.

"Salting out" is a term used to describe the effect on flavor release resulting from adding salt to a system. The presence of salt changes the thermodynamic state of the system, altering the partition coefficients for many compounds. Each compound will not be affected equally: some compounds' volatility will be increased, others suppressed, and some may be unaffected. Since ionized compounds do not volatilize, changing the ionic state of a system, eg, by adding salt or adjusting acidity, will selectively influence the volatility of ionic odorants.

Thermodynamic parameters, eg, equilibrium coefficients, describe the potential degree of volatility of each compound. Since the process of eating takes place under dynamic conditions, sampling the headspace of food in a sealed jar at equilibrium will not be representative of the ratio of compounds found at the olfactory epithelium during eating. Henry's law describes volatility for real solutions at low concentrations and is often applicable for aroma compounds since they are almost always present at very dilute levels (eg, ppm). To calculate the equilibrium coefficient for an aroma compound in a real food system, either the first viral constant or the Henry's law constant needs to be known. Few Henry's law constants or viral constants for aroma compounds are published, thus they must be measured before calculating the volatility. Further, the rate of volatilization plays an important role in defining flavor release in this nonequilibrium system. The composition of volatiles that reach the olfactory receptors depends on how fast each aroma compound volatilizes in the short time that the airflow is in contact with the bolus prior to traveling through the nasal pharynx (retronasal route) to produce a response. Rates are more complicated when there are multiple binding sites on a single molecule as with proteins and polysaccharides. Additional constraints on the system come from viscosity and surface tension.

For an accurate kinetic description of flavor release from a simple grape beverage containing water, sucrose, gum, and two aroma compounds, there would be 17 rate equations and 10 variables necessary to define the state. A typical commercial soda would have ~300 rate equations and 60 variables to define the state. Since the rate constants are not generally available, each would have to be measured. Most food systems are complex, containing many components, thus empirical assessments may be more feasible for most industry applications. Some predictive calculation tools have been developed; however, these are food system dependent and cannot account for all real parameters effecting flavor release.

Conditions in the mouth during eating (*in vivo*) can affect aroma volatility and thus the ratios and quantities that reach the olfactory epithelium (59). Mastication of solid foods affects volatility by accelerating mass transfer out of the solid matrix with highly variable shear ranging from 10 to 500 s-1. Air flow from breath carries the odorants to the olfactory receptors at a rate of ~100 mL/s, stripping the odorants from the bolus at varying rates. Temperature further defines the state of the system. Heating a system will increase the release of all compounds in accordance with the ideal gas law. Saliva dilutes the sample, affects the pH, and may cause compositional changes through the action of the enzymes present given enough exposure time. Several devices or mouth simulators have been developed to simulate the conditions in the mouth that affect flavor release for the purpose of measuring the resulting volatile concentration (59,60). These systems account for the effects of salivation, chewing, and temperature change of the food after it enters the mouth.

Air flow has been shown to be the most influential on flavor release, thus any mouth simulator needs to provide similar air flow rates as human breath (2). For a liquid food system, constant stirring, eg, with a magnetic stir-bar may be sufficient to account for mastication. For foods with several phases (eg, pastries or vegetables), a device capable of breaking up the food releases the volatiles similar to mastication. A blender with controlled airflow through the vessel and a heated water jacket is the foundation of the retronasal aroma simulator (RAS) developed by Deborah Roberts and Terry Acree at Cornell University (56). Simulation systems drastically improve reproducibility resulting from the high variability that may occur between human subjects (2), this indirect method of estimating flavor release typically cannot account for the parameter of time.

Atmospheric pressure ionization mass spectrometers (APIMS) and proton-transfer reaction mass spectrometers (PTRMS) are sophisticated instruments capable of measuring flavor release *in vivo* (61–66). A heated tube with a venturi air flow draws the volatile compounds during exhalation from the nose delivering the volatiles directly into the ionization source with no prior chromatographic separation. Ionization conditions are set so that formation of the protonated molecular ions is favored. Real time profile of flavor release are measured with these systems, providing additional information related to the parameter of time.

Other techniques must be used in conjunction with the *in vivo* analysis for chemical identification and differentiations of odor active compounds.

3.2. Odor Activity. Despite the fact that often hundreds of volatile compounds are present in a food, only a few may be odor active. This criterion greatly reduces the number of compounds to be considered in flavor analyses, but also makes incorporation of a human sensory component essential in differentiating odor active and nonodor active compounds. There are <1000 compounds that, at levels found in food, are known to be odor active. To selectively identify compounds that could potentially contribute to the flavor, humans must be used as detectors. Gas chromatography olfactometry (GCO), where the effluent from the GC column is sniffed by a person, has been used for >50 years and gives a direct link between chemical and sensory analyses. This is the most fundamental tool for a chemist studying flavors and fragrances. Decades ago, chemists would use a GC chromatogram (detected by FID or mass spectrometry) to describe a "flavor". These chromatograms fall short without a differentiation of odor active and nonodor active compounds. Usually, the nonodor active compounds are predominate quantitatively, while compounds with potent odor contribution may have insignificant quantitative contribution to the mixture. Basic GC traces can be useful for quality assurance and comparisons once the odor active compounds have been identified.

The combinatorial nature of the olfactory receptor system complicates the efforts to identify the structural correlations to interact with one of the ~400 types of olfactory receptors (25,67). The relationship of some compounds and specific olfactory receptors has been elucidated in rats and fish. New understandings are rapidly being uncovered in this area, while the elucidation of human receptor–chemical structure correlations will likely be accomplished shortly. Chirality is important to perception with several chiral isomers imparting very different aroma characters to carvone (Fig. 4) (68–70). Perceived character may also be affected by concentration, eg, for methyl isoborneol at ppb levels has a dirt-like aroma; while at ppm and higher concentrations smell camphoratious.

3.3. Concentration. Some psychophysical laws of thresholds were addressed in the section Psychophysical Precepts. Many compounds that have potential to stimulate an olfactory response may be present, but only a fraction of them may be present at high enough concentrations to create a perception, ie, present above their detection threshold. A common mistake is to describe a threshold within one system, eg, water, and interpret that to be the odorant's threshold in all systems. It is in fact, the threshold concentration in that system only and is influenced by flavor release. Even the relative thresholds will be different in different systems partially due to flavor release. When headspace measures are made from samples under mouth conditions, thresholds in air are more interchangeable across various food compositions. To further complicate threshold measures, detection thresholds change as an individual has repeated exposure (eg, the section Adaptation).

3.4. Summary. Aroma chemical investigations encompass aroma compound identification, potency, and intensity measurements, combined with the determination of the contribution of an aroma compound to the overall flavor perception. The nature of odorants introduces a variety of challenges for analysis. Odorants must be volatile in the context of eating or drinking; therefore, sampling of the gas phase and control of temperature, air flow conditions, and mixing must be accounted for (59). Selecting for the relatively few odor active compounds among the often hundreds of volatile compounds in a food, requires methods to differentiate between odor active and nonodor active compounds. The GCO has been an invaluable tool for separation and subsequent identification of odor active volatile compounds.

4. Analysis of Aroma

The chemist undertaking flavor analysis is faced with some unique parameters to take into consideration. Chemical attributes (eg, volatility) and physiological attributes (eg, human detection limitations) should be accounted for in the design of the experiment. Carefully defining the purpose of the analysis allows the chemist to design a study tailored specific to the situation. Very different approaches and tools may be used dependant on the intention of inquiry. Effective analysis require an integration of instrumental techniques with sensory assessment. Accounting for human perception is paramount in any aroma analyses. *Sensory Evaluation of Food: Principles and Practices* by Harry Lawless and Hildegarde Hemann serves as an excellent reference focusing on sensory analysis (71).

4.1. Characteristics Imparting Analytical Challenges. Some characteristics of aroma compounds along with perceptual characteristics require consideration for analyses including present at trace amounts (ppm to ppt levels) thus often requiring concentration; only a few compounds have odor activity at levels found in food; compounds must volatilize into the gas phase; interaction with food matrix—flavor release; affected by conditions during eating and drinking—mouth context; detection threshold; precision of chemical measurement versus variability of sensory measurements; neurology, eg, specific anosmia, focus, translation into linguistics, adaptation; synergy and suppression with other senses.

There is no single procedure or technique to address all aroma analyses situations. The experimental design for an aroma analysis should be driven by the chemical characteristics, psychophysics, together with a clear understanding of the objectives of the investigation. Present at trace levels in complex food systems, aroma chemicals may require extraction and concentration. All extraction and concentration methods exhibit some degree of selectivity and introduce a potential for degradation of aroma components and artifact formation (72,73). Some methods of extraction and concentration include vacuum distillation, simultaneous distillation–extraction, solvent–supercritical fluid extraction, Likens–Nickerson extraction, SAFE (a modified Liken–Nickerson method), and Mixxor liquid extraction (74–79). Volatility characteristics are critical in determining the contribution of a compound to the overall perception. Nonaroma constituents of foods can influence the degree to which a particular compound volatilizes (flavor release) thus affecting the ratio of volatilized compounds.

Headspace extraction techniques introduce potential absorptivity, selectivity, and equilibrium. Being aware of how these factors affect a gas-phase extraction is critical in interpreting the resulting data (80). Some methods of gas-phase extraction include static headspace, dynamic headspace purge and trap, and solid-phase microextraction (SPME) (81,82).

Most foods contain hundreds to thousands of volatile compounds; however, only a small fraction (on the order of 10–30) impart the aroma perception. To selectively identify odor active compounds, humans must be used as detectors (1). Gas chromatography olfactometry, human sniffing of the effluent leaving the GC, has been used for >55 years and gives a direct link between chemical and sensory analyses. Methods for determining relative aroma potency of compounds using GCO have been well established (CharmAnalysis, AEDA, odor units). Focusing on the small subset of volatile compounds with the highest odor potency has proven useful in comparing products under different troubleshooting situations. *In vivo* methods allow for the monitoring of preidentified volatile compounds during food consumption enabling simultaneous sensory and chemical analyses and correlation. An example of *in vivo* instrumentation is the MSNose that uses a Platform LCZ quadrupole mass spectrometer operating in the atmospheric pressure ionization (API) positive ion mode fitted with a venturi heated air-sampling interface (61).

Even a minimal sensory component is required in any analyses of aroma. The human olfactory systems is exceedingly sensitive down to picograms in liter concentrations for some compounds. This sensitivity transcends that of even modern instrumentation, giving further need for concentration and extraction (Fig. 5). Detection thresholds and just noticeable difference measurements can be used for approximation predictions of perception. Large differences or changes are required to perceive a difference, alleviating the need for tight precision in chemical measures. The variation between humans need not be overwhelming provided it is understood that the results are approximations under defined parameters. An approach to minimize the impact of the high variation in detection thresholds has been to select people based on their olfactory responses to a set of compounds (83–85). Ultimately, it may be possible to normalize panelists based on their olfactory genome as the genomic research advances.

4.2. In-Depth Determination of Aroma Impact Components of a Food. Progression of a thorough flavor chemical analysis to identify aroma compounds that contribute to a specific system's aroma perception correlates chemistry with sensory data following the below series of analyses:

1. Sample preparation representing *in vivo* ratios.
2. GCO single sniff analysis.
3. GCO dilution analysis.
4. Component identification.
5. Descriptive analysis of N-dimensional component mixtures.
6. n-1 sensory descriptive analysis (omission study) (86).

EXAMPLE OF AN AROMA ANALYSIS

Problem: Dirt-like off-aroma found in a single production of a beverage.

Experimental design considerations: The purpose of the investigation was ultimately to find and eliminate the source of the off aroma. To identify the compositional cause of the off-odor, the analysis neither needed to be quantitative, nor strictly representative of retronasal ratios.

1. Extraction and concentration: The beverage was extracted with ethyl acetate and concentrated by a factor of 300 using a rotary evaporator (eg, rotavap).
2. Selectivity for odor activity, GCO: The extracts from the control and sample beverage were sniffed by one person as the components eluted from the GC. A distinctive "dirt-like" odor was detected at a retention index of 1410 from the extract of the off-odor sample, and no odor was detected at this retention index from the extract of the control sample. All other odor character and retention index were the same from the control and the off-odor extracts.
3. Identification of the select odor component: Reference to the FlavorNet (//www.flavornet.org/) showed that geosmin [*19700-21-1*] had been found by GCO analysis to have a "beet, earth" odor character and a Kovats retention index of 1412. The GC/MS of the component was inconclusive. No component could be detected between 1390 and 1430 retention indices. The GCO of a standard of geosmin at 0.05 ppm (w/v) in ethyl acetate and the sample separately using two different types of columns (DB-5 and Carbowax), resulted in elution of a component of the same odor characteristic at the same time, eg, on the DB-5 column at a retention index of 1410 the same odor was detected in the standard and the sample. On the carbowax column at a retention index of 1770 the same odor was detected in the standard and the sample.

This evidence is conclusive that the off-odor was caused by geosmin, which has been reported to form in water from *Oscillatoria simplicissima* and *Anabaena scheremetievi* contamination.

Another rapid extraction and concentration technique that would have been applicable is SPME of the headspace under static condition (82); however, extra care would be necessary for replication and greater concentration could be achieved with the solvent extraction. Additional chemical separation and detection techniques could have been used to elucidate the identification of the component, eg, multidimensional chromatography, nuclear magnetic resonance (nmr), and infrared (ir). Geosmin has such a low odor detection threshold, that it can be detected by the human nose, while being below the detection limits of a mass spectrometer from this sample.

Had a single characteristic component not been identified in the initial GCO comparison of the standard and the sample, comparison of the approximate relative quantitative values of the odor-active compounds may begin to demonstrate some differences. Sampling under conditions more representative of human physiology and application of a potency measurement technique, eg, CharmAnalysis, may be useful.

5. Taste

Chemoreceptive events in the mouth lead to taste perception (87). Taste is typically described by five modalities coupled with chemesthesis: salt, sour, sweet, bitter, and umami (88). Chemicals detected throughout the oral epithelium by activating the trigeminal nerve produce chemesthesis. Chemesthesis may be described as pungency, astringent, cooling, pain, etc. For the remaining five tastes, chemicals activate taste receptor cells that occur singly or densely packed in taste buds found on the palate, pharynx, epiglottis, larynx, and esophagus (89). The myth of topographical regions on the tongue for detection of each taste where sweet is detected at the tip of the tongue, bitter at the back, is a mistranslation of work reported in the early-1900s. All taste qualities are perceived all over the tongue, though there may be increased sensitivity in certain areas (88,90). Quality, intensity, and hedonics (like or dislike) can characterize taste.

The taste neurological receptor system is distinctly different from olfaction. For a good review of the current understanding of taste receptors see Chandrashekar et al. (91). Within a bipolar taste cell, the receptor protein is mounted on a microvilli that extends into the oral cavity; the other end of the taste cell sends synapse signals to the brain stem processing into a perception. Taste receptor cells live $\sim$10 days. Sweet and umami tastes have overlapping receptor systems sharing one receptor type. This shared receptor combines with a different second receptor to differentiate between the two modalities. About 30 receptors are involved in *bitter* taste detection. Saltiness and sour are responses to ionic potential. Table 2 summarizes the current understanding on a number of receptor types for each chemical sense and typical magnitude of concentrations.

Several aspects affect the extent and character of taste. As with aroma, after constant stimulation exposure to a tastant, adaptation occurs; where the presence of a tastant is no longer consciously perceived. Enhancement and suppression may occur when multiple taste stimuli are present (92,93). For example, the saltiness of sodium chloride is reduced by sucrose, while it can be significantly enhanced by acid. Genetic factors influence an individual's taste perception. A classic example is of "taster" and "nontasters" of Phenylthiourea (PTC) (94–96). Phenylthiourea causes a distinct bitter sensation for some, but others have no detection of it even though their ability to distinguish other tastes is not noticeably impaired.

Tastants must be in water solution to produce a taste perception. Saliva may serve as the buffering water source for dissolving, diluting, and transporting the stimulant. The enzymes in saliva may also potentially cause rapid chemical changes in food ingredients, eg, proteins and carbohydrates. However, the effect is minimal, if any, from enzymes on beverages and other foods that require little or no mastication before swallowing. Learned association with other senses may bias a perception, eg, vanilla aroma interpreted as sweet and creamy.

5.1. Salty Taste. Only salts are salty; however, not all salts are salty (88). Some are sweet, bitter, or tasteless. Monovalent cations, especially sodium (Na^+), can pass directly through ion channels in the tongue, leading to an action potential leading to the salty percept. Sodium chloride (table salt) in foods may be analyzed using a specific ion electrode. To measure other salts, ion chromatography or atomic absorption emission spectroscopy are generally used.

5.2. Sour Taste. Sourness indicates acidity, though not all acids are sour. The detection of acids facilitates maintaining the body fluid compositional balance. The pH is characteristic of the carbon dioxide levels in blood and cerebrospinal fluid. To some extent, the intracellular pH of taste cells follows extracellular changes in pH. Two groups of sour taste receptors have been identified. One mechanism, the intracellular pH of the taste cells, follows extracellular changes in pH through ion channels. The other mechanism utilizes proton gated channels.

Neither titratible acidity nor pH, fully correlates with sourness, but the perception is a function of the entire acid molecule. For example, malic acid (from apples) has a distinct sour perception from citric acid (from citric fruits). Ion chromatography may be used for analysis of sour components.

5.3. Sweet Taste. Two types of receptor systems correspond with sweet taste; one responds to certain carbohydrates and the other to high potency sweeteners (eg, artificial sweeteners) (97). The structural requirements for a compound to activate sweet receptors have not been fully defined. In ~1970, Shallenberger and Acree described a structural commonality of sweet carbohydrates to all contain an AH,B system, where a hydrogen-bond donor (AH) and a Lewis base (B) are present and separated by ~0.3 nm (98). More recent studies have elucidated the genetic coding and receptor system for sweet reception of carbohydrates. The larger high potency sweet molecules activate a overlapping yet different mechanism. High pressure liquid chromatography (hplc) is a key tool used in analyzing sweet components.

5.4. Bitter Taste. Some have speculated that bitter taste serves as a deterrent from poisonous foods; however, we enjoy many bitter foods, eg, coffee. Many different types of molecules produce a bitter taste including divalent cations, alkaloids, and some amino acids (88,95). With >30 receptor systems for bitterness, it is the least discriminating of the taste modalities. Bitterness could arguably be broken down into several additional taste classification. Due to the broad range of chemical structures, multiple analytical approaches may be necessary to analyzing bitter components, though hplc is often applicable.

5.5. Umami Taste. Umami is the taste of a few amino acids (eg, glutamate, aspartate, and related compounds) and was classically not included as a taste modality (99). Sometimes described as savory, brothy, or meaty, it is the dominant taste of such foods as chicken broth, meat, and ageing cheese. Umami perception results from activation of two receptor systems, with one that overlaps with the receptor systems for artificial sweeteners (100,101). There are many hplc systems that integrate sample preparation along with data analysis specific to amino acid analysis.

5.6. Chemesthesis. Chemesthesis in the mouth is the chemical irritation (eg, pain, heat, cooling) due to stimulation of the trigeminal nerve (102). Chemesthesis also occurs in other parts of the body including the eyes, nose, and throat. Some examples of chemesthesis are burning from jalapenoes, cooling from mint, and pain from carbonation.

6. Flavor Materials and Compounding

Flavor in food can be innate, formed, and added. Flavors are formed when food is heated, fermented, and mixed with reactive ingredients. Storage condition and age may modify the flavor, eg, by oxidation, ultraviolet (uv) exposure, and interaction with packing material. *Flavorings* are mixtures combined or "compounded" from substances intended to impart a flavor, modify a flavor, or mask an undesirable flavor (103).

6.1. Formation. Elucidating the formation pathways for aromas in foods was an early focus of flavor research. However, many proposed mechanisms do not take into consideration that the aroma compounds are usually present at trace amounts and thus are likely results of intermediates, reverse reactions, or minor reaction routes requiring high energy inhibitive to be a primary mechanism. To identify the mechanism, one must look for a major components' pathway with a minor high energy equilibrium route (ie, by-products). For example, Maillard reactions are often attributed for the formation of aroma compounds (104); however, the described kinetics often do not correspond with the low levels formed.

Fermentation results in the enzymatically catalyzed formation of flavors in foods eg, alcoholic beverages, cheese, pickles, vinegar, bread, and sauerkraut. In some vegetables, eg, onion and garlic, the flavor components are released enzymatically when the tissue is crushed or broken. Fruit flavors are developed during ripening.

6.2. Adding Flavoring

Flavorists. A creative flavorist, sometimes referred to as a flavor chemist, is an individual who has undergone a rigorous training overseen by the Society of Flavor Chemists, entailing a 7-year apprenticeship period and a review by the organization. Similar programs exist internationally. The flavorist need not have a formal chemistry background, but it can be helpful. Chemists, sensory scientists, and other experts work together with flavorists to formulate flavor ingredients and monitor quality.

Flavorings are the flavorists' pallet. Flavorists "compound" ingredients to meet a food designer's request for a specific product application, using creative and artistic talents along with analytical support. Compounding usually follows a predominantly empirical process that may be directed and assisted by flavor chemical and sensory analyses. Utilization of flavor release analyses can reduce the number of iterations necessary during some formulations. The flavorist selects materials takings into consideration the type of product, conditions of manufacture, labeling, and intended use.

Flavoring Materials. Synthetic flavor components, essential oils, concentrated oils, and oleoresins are some of the forms of flavoring material used by the flavorist. Different solvents used for extraction, pressing, and distillation result in different flavor compounds being extracted. Some solvents commonly used include water, low boiling point nonpolar solvents (eg, ethanol, ether, cyclohexane, methylene dichloride), and liquefied carbon dioxide. The solvent may or may not be present in the final flavoring preparation. Different parts of the plants can be used to obtain essential oils, including the flowers, leaves, seeds, roots, stems, bark, wood, peel, etc.

7. Regulations in the United States

Which flavor ingredients are permitted to be used in foods and required labeling are regulated by the U.S. Food and Drug Administration (FDA) in the Code of Federal Regulations (CFR) Title 21 (105). Food additives, eg, flavorings, must be demonstrated as safe through an extensive petitioning process; however, if the food additive falls into one of two classes, it is exempt from this requirement (21 CFR 170). The two categories of exemption are materials sanctioned for use prior to 1958 (when the Food Additives Amendment was passed) and materials Generally Recognized As Safe (GRAS) by the scientific society. General recognition of safety through experience based on common use in foods requires a substantial history of consumption for food use by a significant number of consumers. Since aroma compounds are present at such low levels, use of technology with increased sensitive may demonstrate that a material has been present in foods for an extended period of time and thus some flavoring materials may still be added to the list of food additives approved for use based on this criteria. The use of a substance, rather than the substance itself, is eligible for the GRAS exemption. The FDA has defined “safe” as a reasonable certainty in the minds of competent scientists that the substance is not harmful under its intended conditions of use. The specific data and information that demonstrate safety depend on the characteristics of the substance, the estimated dietary intake, and the population that will consume the substance.

The flavor and fragrance industry has been largely self-regulated. The regulations allow for GRAS determination to be made by an independent, qualified panel of experts in pertinent scientific disciplines formed by the manufacturer. The Flavor and Extract Manufacturers Association (FEMA) supports its industry with evaluation of materials for GRAS status. The FDA has not challenged the marketing of flavors that FEMA has identified as GRAS, whether or not it has incorporated them into its own lists of GRAS substances or approved food additives. The FDA actually occasionally refers to FEMAs GRAS listing of a flavor to support a GRAS affirmation proposal.

Regulations related to flavoring ingredients are quite different internationally and frequently modified. The United Nations Food and Agriculture Organization and the World Health Organization (WHO) formed the Joint Expert Committees on Food Additives (JECFA) to provide independent scientific expert advice to the Codex Alimentarius Commission. The JECFA reports have influenced decisions by the FDA and other regulatory bodies, and its recommendations concerning particular additives might be relied upon by companies in making GRAS self-determinations.

For consumer products, specific labeling criterion are defined in relation to flavors primarily in 21 CFR 101. The product characteristic flavor and natural status of flavors must be listed on the Principle Display Panel (PDP). Size, location, wording, and imagery, are specified in the regulations. Addition of flavorings must be listed in the ingredient statement as further specified.

Natural and artificial flavors' classifications are defined in 21 CFR 101.22 as: "... a natural flavor is the essential oil, oleoresin, essence or extractive, protein hydrolysate, distillate, or any product of roasting, heating, or enzymolysis, which contains the flavoring constituents derived from a spice, fruit or fruit juice, vegetable or vegetable juice, edible yeast, herb, bark, bud, root, leaf or similar plant material, meat, seafood, poultry, eggs, dairy products, or fermentation products thereof, whose significant function in food is flavoring rather than nutritional". Artificial flavors are any substance or substances, the function of which is to impart flavor, which are not derived from natural sources.

Many artificial flavor chemical components also occur in Nature, ie, Nature identical. The FDA explains that an artificial flavor is no less safe, nutritious, or desirable than a natural flavor, and that the purpose for distinguishing between a natural and artificial flavor is for economic reasons. Examples of flavor chemicals that exists both as natural and artificial flavoring include benzaldehyde made synthetically or obtained from oil of bitter almond; and L-menthol made synthetically or isolated from oil of *Mentha arvensis var*.

8. Select Sources of Current Flavor Information

Flavor research is constantly evolving, as such, resources that provide reliable and progressive flavor research information, help one remain current on what is at the forefront in this ever changing field. The following is a compilation of some reputable sources of flavor research information. This is not intended to be an all inclusive listing, but serves as initial direction to find current information in flavor chemistry.

9. Journals

Journal of Agricultural and Food Chemistry (pubs.acs.org/journals/jafcau): The *Journal of Agricultural and Food Chemistry* publishes research results dealing with the chemistry and biochemistry of agriculture and food. This journal also reports on the chemical processes involved in nutrition, phytonutrients, flavors, and aromas.

Chemosensory Perception (www.springer.com/12078): *Chemosensory Perception* is a new peer-reviewed journal that publishes original research and review papers covering the connection between chemical, sensory, and neurological sciences. Particular emphasis is placed on interdisciplinary work linking these areas. Only animal work with explicit links toward human phenomena are included.

Chemical Senses (chemse.oxfordjournals.org): *Chemical Senses* publishes original research and review papers on all aspects of chemoreception in both humans and animals. An important part of the journal's coverage is devoted to techniques and the development and application of new methods for investigating chemoreception and chemosensory structures.

LWT—Food Science and Technology (Lebensmittel-Wissenschaft und–Technologie) (www.elsevier.com): *LWT—Food Science and Technology* is an international journal that publishes innovative papers in the fields of food chemistry, biochemistry, microbiology, technology, and nutrition. The significance of the results either for the science community or for the food industry are specified.

Journal of Food Science (members.ift.org/IFT/Pubs/JournalofFoodSci): The *Journal of Food Science* (JFS) is the Institute of Food Technologist's (IFT) science journal, publishing reports of original research, and critical reviews of all aspects of food science.

Journal of the Science of Food and Agriculture (http://www3.interscience.wiley.com/cgi-bin/jhome/1294): *Journal of the Science of Food and Agriculture* publishes research and reviews related to food and agriculture, pharmaceuticals, biotechnology, materials, chemicals, environmental science and safety, with particular emphasis on interdisciplinary studies at the agriculture/ food interface.

Flavour and Fragrance Journal (http://www3.interscience.wiley.com/cgi-bin/jhome/4029): The *Flavour and Fragrance Journal* publishes original research articles, reviews and special reports on all aspects of flavor and fragrance. Emphasis is placed on analytical aspects and the important role that analysis in its widest sense plays in the support of research and applications. The coverage of the journal includes a wide range of product types, eg, fragrances and their compositions, and the flavor, colors, and odors of foodstuffs.

Journal of Essential Oil Research (http://www.perfumerflavorist.com/jeor): The *Journal of Essential Oil Research* (JEOR) includes publications relating to essential oil research and analysis. Each issue includes studies performed on the chemical composition of some of the 20,000 aromatic plants known in the plant kingdom.

Perfumer & Flavorist (www.perfumerflavorist.com): *Perfumer & Flavorist* magazine reports the latest news and developments in the flavor and fragrance industry. Directed to manufacturers and creators of flavors and fragrances and the producers and marketers of essential oils and aroma chemicals, this magazine covers the technology, the art and the psychology of flavor and fragrance development.

Food Technology (members.ift.org/IFT/Pubs/FoodTechnology): *Food Technology* is the monthly publication of Institute of Food Technologsits (IFT). *Food Technology* provides news and analysis of the development, use, quality, safety, and regulation of food sources, products, and processes for food scientists and other interested individuals in the food and supplier industries, government, and academia.

9.1. Websites

www.flavornet.org: The Flavornet is a compilation of aroma compounds found in the human odor space. A seemingly infinite number of perceptions are invoked by <1000 odorants that make up this space. The Flavornet lists only those odorants that have been demonstrated to invoke an aroma perception at suprathreshold levels.

www.leffingwell.com: This Web site offers information on subjects related to Perfume and Flavor Chemistry along with many links related to flavors, fragrance, olfaction, herbs and spices, botanical medicine, as well as organoleptic properties and molecular visualization of selected flavor and fragrance materials.

9.2. Associations and Societies.

The Association for Chemoreception Sciences (AChemS) (www.achems.org): AChemS is an international association aimed at advancing understanding of the senses of taste and smell. Basic, clinical, and applied research in the chemical senses (gustation, olfaction, and trigeminal sensation) research are encouraged. AChemS promotes an appreciation of chemosensory research, represents the interests of the chemosensory research community, and serves as a resource for those requiring chemosensory expertise.

The European Chemoreception Research Organisation (ECRO) (ecro.cesg.cnrs.fr): The European counterpart of AChemS, the goal of ECRO is to promote fundamental and applied research in olfaction and taste in vertebrates and invertebrates.

The Japanese Association for the Study of Taste and Smell (JASTS) (epn.hal.kagoshima-u.ac.jp/JASTSE): The purpose of the Corporation is to advance the development of extensive research concerning Taste and Smell.

American Chemical Society—Agricultural and Food Chemistry Division—Flavor Subdivision (membership.acs.org/a/agfd): The Division of Agricultural and Food Chemistry has a breadth of interests and disciplines that covers the wide spectrum of biotechnology, nutrition, fertilizers, insecticides, fungicides, rodenticides, herbicides, fermentation, crops, flavor, and food technology.

Institute Of Food Technologists (IFT) (www.ift.org): The IFT is a not-for-profit organization whose mission is to advance the science and technology of food through the exchange of knowledge. Its members represent a broad cross-section of food professions in industry, academia, and government throughout the world.

Monell Chemical Senses Center (www.monell.org): The Monell Center is a nonprofit independent scientific institute dedicated to interdisciplinary basic research on the senses of taste, smell, and chemosensory irritation. In addition to increasing fundamental knowledge about the chemical senses, basic research at Monell relates to significant public health and quality of life issues, including obesity, diabetes, hypertension, pediatric health, occupational safety, environmental pollution, and homeland security.

The Sense of Smell Institute (www.senseofsmell.org): The Sense of Smell Institute's mission is to be a leading global resource relating to the sense of smell and its importance to human psychology, behavior, and quality of life. They encourage exploration into the broader multisensory context of smell, including its interplay with taste.

Society of Flavor Chemists—USA (www.flavorchemist.org): The Society of Flavor Chemists (SFC) is a not for profit organization devoted to the advancement of the field of flavor technology and related sciences by (1) encouraging the exchange of ideas and personal contacts and (2) by sponsoring and conducting meetings, lectures, and symposia.

British Society of Flavourists (www.bsf.org.uk): The BSF is a Society made up of individuals whose work involves flavorings. Its objective is to promote the knowledge and art of flavor creation through research and education.

Flavor And Extract Manufacturers Association (FEMA) (www.femaflavor.org): The Flavor and Extract Manufacturers Association furthers the business interests of its members through a sound scientific program designed to promote the safe use of flavors. Through effective representation of its members, FEMA fosters a global environment on which the flavor industry can create, innovate, and compete.

IFEAT—International Federation of Essential Oils and Aroma Trades (www.ifeat.org): The principal activity of IFEAT is the advancement and protection of the rights and interest of Members involved in the essential oil and aroma trades in all parts of the world.

International Organization of the Flavor Industry (IOFI) (www.iofi.org): IOFI is a worldwide federation of national and regional associations whose members represent national and international flavor producers. It operates at the global level and is engaged principally in activities that ensure a supply of safe flavor materials.

Women in Flavor and Fragrance Commerce, Inc. (www.wffc.org): The WFFC, Inc.'s mission is to provide a center of education, camaraderie, support, and networking opportunities for women in the flavor and fragrance industry.

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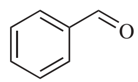
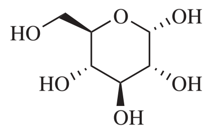
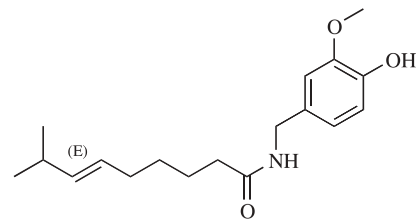
Table 1. **Examples of Stimuli that Impart Aroma, Taste, and Chemesthesis Perception**[a]

Sense	Aroma	Taste	Chemesthesis
percept	almond, cherry	sweet	hot, pungent
chemical	benzaldehyde	glucose	capsaicin
CAS #	[*100-52-7*]	[*50-99-7*]	[*404-86-4*]
structure			
typical concentration	10–5 mM	100 mM	2 mM
size	< 300 Da	< 500 Da	

[a]Refs. 6–8.

Table 2. **The Chemical Senses Range in How Many Ligands Can Induce a Perception, Complexity of Receptor Systems, and Detection Magnitude**[a]

	Number of ligands (stimuli)	Example ligand	Number of receptor systems	Typical magnitude of concentrations
salt	1	sodium	1	NaCl 0.1%
sour	1	hydrogen ion	1	H^+ ion 1%
umami	5–10	amino acids	1	glutamate 1%
sweet	10–20	sugars/artificial sweeteners	2	sucrose 20%/ sucralose 0.01%
bitter	10's	organic bases	30	phenolics 0.01%
odor	100's	organic volatiles	~400	linalool 0.0000001%

[a]Taste detection requires many magnitudes greater concentration than olfaction.

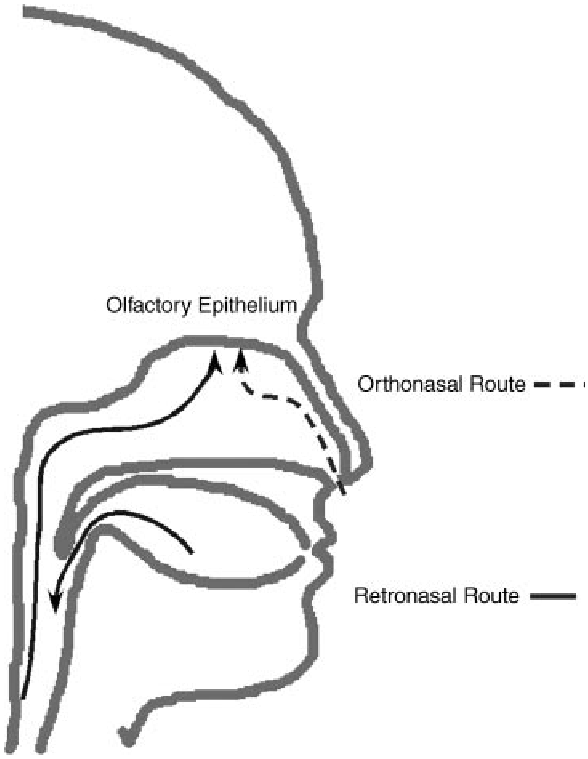


Fig. 1. Volatiles follow two pathways to reach the olfactory epithelium to potentially impart odor or aroma perception. Orthonasal route is followed when smelling and the retronasal route via the nasal pharynx is followed from the mouth when eating or drinking.

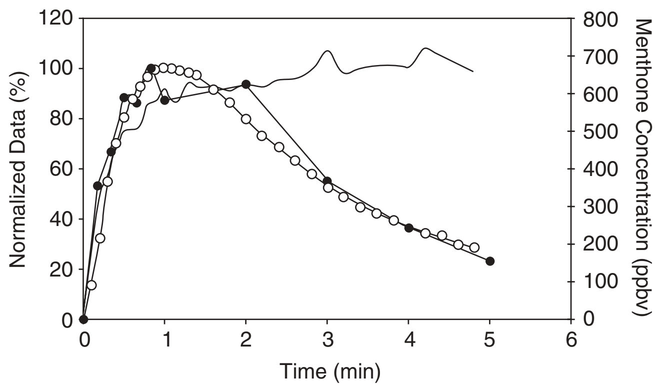
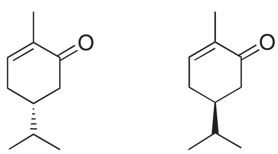


Fig. 2. Sucrose release (b), menthone release (s), and perceived intensity of overall mint flavor (TI curve) (O), from a stick type commercial chewing gum. [Reprinted with permission from Ref. 33. Copyright 1999 American Chemical Society.]

Fig. 3. Neurological processing of olfaction is affected by attention similar to the processing of the old woman–young woman optical illusion. In this figure, one may see an old woman or a young woman depending on attention. The old woman's mouth is the young woman's necklace. The old woman's nose is the young woman's chin. They share their hair, the scarf, the fur coat, and the feather in their hair.



(+) *d*-carvone
[2244-16-8]
Caraway

(-) *l*-carvone
[99-49-0]
Spearmint

Fig. 4. Enantiomers of some odorants results in different perception. *d*- and *l*-Carvone have distinctly different odor characteristics.

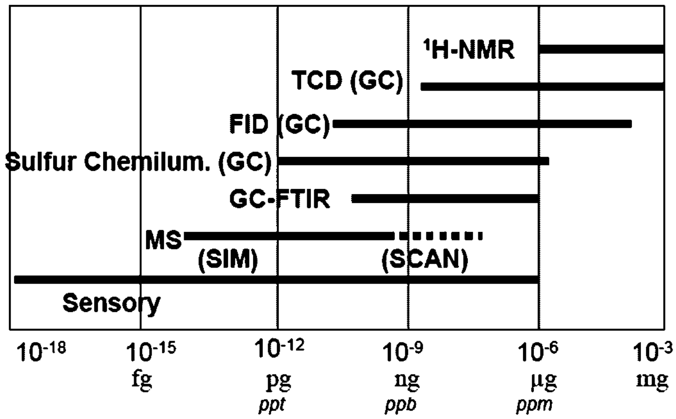


Fig. 5. Comparison of instrumental sensitivities to flavor detection. [Modified reproduction with permission from R. J. McGorrin *Analytical Chemistry of Flavors* presentation at ACS Flavor Research Workshop, Washington, D.C., 2005, August 26–27.]