Polyphenols: factors influencing their sensory properties and their effects on food and beverage preferences¹–³

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ABSTRACT
Bitterness and astringency are found in a variety of foods, including nuts, fruits, chocolate, tea, wine, and soymilk. In fruits and beverages, the taste of bitterness and the tactile sensation of astringency are elicited primarily by flavanol polymers (proanthocyanidins or condensed tannins). Variations in proanthocyanidin composition, such as polymer size, extent of galloylation, and formation of derivatives, affect both bitterness and astringency. In beverages, other factors also influence these sensations, including the pH and the levels of ethanol, sweetness, and viscosity. Similarly, foods eaten with beverages can influence astringency. For example, eating dark chocolate increases the astringency of red wine more than does milk chocolate. Individuals perceive astringency differently because of variations in salivary flow rates, and preferences for and acceptance of a product may vary tremendously among individuals; decreasing bitterness and/or astringency may not increase preference. Factors influencing bitterness, astringency, and individual preference decisions are discussed.


KEY WORDS Polyphenols, astringency, bitterness, sensory perception, consumer preference

INTRODUCTION
In the past decade, there has been growing interest in nutraceuticals and functional foods in Western countries. Many new products focused mainly on ingredient functionality and not on sensory properties. Consumers anticipated and accepted an unbalanced flavor, as long as the product delivered health benefits. In fact, many consumers thought that, if the product tasted bad, then it was obviously good for you. Consumers now want both health benefits and palatable food.

Flavanol polymers are being actively studied because of their cancer prevention properties and other potential nutritional benefits. However, their sensory properties can be summarized with 2 main descriptors, bitterness and astringency, which are well known for eliciting negative consumer reactions when present at high intensity. Factors influencing bitterness, astringency, and individual preference decisions are discussed here.

SENSORY PROPERTIES OF POLYPHENOLS

Compounds responsible
In beverages such as tea, cider, and red wine, as well as in several types of fruits, nuts, and chocolate, the taste of bitterness and the tactile sensation of astringency are elicited primarily by the flavonoid phenols, including flavans and flavonols. Of these, the flavan-3-ol monomers (catechin, epicatechin, epigallocatechin, epicatechin gallate, and epigallocatechin gallate) and their oligomers and polymers, which are called proanthocyanidins or condensed tannins, are the most abundant in wine and tea. Both procyanidins (polymers of epicatechin and catechin) and prodelphinidins (polymers of epigallocatechin) have been detected in grapes (1, 2), whereas tea contains monomers and polymers of all 5 flavanols (3). With the exception of the bitterness of caffeine in tea, the flavanols are the primary sources of bitterness and astringency in tea and red wine.

Bitterness
Bitter taste is elicited by structurally diverse compounds, but no clear definition of the molecular properties that confer bitterness has been proposed (4, 5). Taste receptor cells are primarily associated with papillae on the tongue. Several transduction mechanisms for perception of bitterness have been identified and appear to be compound specific (6). Although the mechanisms through which bitter taste perception occurs are not well understood, they are the focus of intensive research, as reviewed elsewhere (7, 8).

Astringency
The tactile sensation of astringency is thought to be perceived through touch, via mechanoreceptors (9). Astringency is described sensorially as a puckering, rough, or drying mouth-feel, whereas an astringent is defined chemically as a compound that precipitates proteins. For water-soluble phenols, molecular weights between 500 and 3000 were reported to be required (10). Consistent with this definition, the assay for tannins developed by Adams and Harbertson (11) can detect only tannins that have >3 flavan-3-ol units. Despite the inability of phenolic compounds with molecular weights of <500 to precipitate proteins in chemical assays, flavan-3-ol monomers (12–14), flavan-3-ol dimers and trimers (15), and hydroxybenzoic acids (16) have been shown to elicit the sensation of astringency. Astringency of

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these smaller phenols may arise from formation of unprecipitated complexes with proteins (17) or cross-linking of proteins with simple phenols that have 1,2-dihydroxy or 1,2,3-trihydroxy groups, as proposed by McManus et al (18). Clifford (19) has provided an excellent review.

FACTORS AFFECTING THE SENSORY PROPERTIES OF POLYPHENOLS

Sensory methods
Evaluation of astringent products such as red wine or tea cannot be made in typical side-by-side comparisons. The intensity of astringency, as well as that of bitterness, builds up when several samples are tasted. Correspondingly, astringency increases with many sips of the same sample. Single-sip time-intensity protocols, in which the judge rates intensity from the time the sample is sipped until the sensation is no longer perceived, minimize carryover effects somewhat but do not reflect perception during normal consumption of beverages. The build-up of astringency has been illustrated in studies in which judges repeatedly sip astringent solutions, at defined intervals, while continuously rating astringency (20). As shown in Figure 1, the maximal intensity of astringency increased with repeated sipping of red wine at 25-s intervals (20). At each sip, astringency increased rapidly, reaching a maximum 6–8 s after the wine was swallowed. Intensity then decreased until the next sip was taken, whereupon another rapid increase occurred. However, increasing the time between sips to 30 s considerably reduced the enhancement of astringency with the second sip (21). A similar trend was observed when a significant increase in astringency occurred when red wines were sipped at 20-s intervals, whereas the increase in astringency with 40-s intervals was not significant (22). Astringency could continue to build during 8 sips, as shown for tea. Similar to the findings for red wines, the maximal intensity for each sip and the minimal astringency value between sips increased as the number of sips increased. However, the increase with each successive sip was not significant after the third sip, suggesting that a plateauing effect might have occurred by sip 3, in contrast to red wines, for which the increases for 4 sips were significant (20).

Chemical structures
Astringency increases and bitterness decreases with the mean degree of polymerization. In addition, small differences in flavonoid configurations can produce significant differences in sensory properties. Epicatechin is more bitter and astringent than its chiral isomer catechin (12, 14). Similarly, the bond location and the identity of the monomeric units influenced the astringency and bitterness of synthesized dimers and trimers (Figure 2). Although the trimers and 2 of the dimers were more astringent than the monomers, dimer B6 (catechin-4,6-catechin) was more bitter and astringent than dimer B3 (catechin-4,8-catechin) and dimer B4 (catechin-4,8-epicatechin) (15).

Vidal et al (23) studied the effects of tannin structure on bitterness and astringency. They showed that modifying the molecular structure by introducing an ethyl bridge decreased astringency but increased bitterness. In contrast, for grape seed tannin, reducing the level of esterification with gallic acid only decreased astringency.

Interactions in mixtures
Increasing the ethanol concentration of wine from 8% to 14% (by vol) approximately doubled the bitterness intensity but had no effect on astringency (24, 25). Ethanol enhancement of bitterness was also observed with model solutions (26). Lowering the pH of wines increased sourness but had no effect on bitterness (27). In contrast, adding acid (and concomitantly lowering the pH) has been reported to increase the astringency of cranberry juice (28), wines (25, 29, 30), and phenolic compounds in model solutions (25, 29–31).
Typically, sweetness and bitterness are mutually suppressed in mixtures (32, 33). Independently increasing sweetness or viscosity decreased the intensity of bitterness in vermouths (34). Adding aspartame to model solutions of grape seed tannin decreased bitterness but had no affect on astringency (35). Conflicting with this, the addition of aspartame to red wine (36) decreased astringency significantly, as did the addition of sucrose (37). When grape seed tannin, citric acid, and alum were thickened with carboxymethylcellulose, astringency was significantly reduced with a viscosity increase of 5 cp (35, 38) (Figure 3). Similar reductions in astringency were demonstrated in carboxymethylcellulose-thickened alum solutions (39), cranberry juice (28), and soymilk (40).

Very little work has addressed the effects on astringency arising from interactions between food and wine. In one study, the astringency of 3 red wines increased after chocolate was tasted, but the increase was much larger after dark chocolate was sampled than after milk chocolate (Figure 4) (A Svensson, unpublished information). In a separate study, the sourness and bitterness of chardonnay wines decreased slightly after hollandaise sauces were tasted, with a larger effect being observed with a higher-fat sauce (41). Interestingly, both the chocolate and hollandaise sauce had larger effects on the wine flavor than the wine had on the flavor of the foods.

**PHYSIOLOGIC FACTORS**

**Propylthiourea/phenylthiocarbamide status**

The wide range of individual sensitivities to the bitter compounds phenylthiocarbamide and propylthiourea has been extensively documented (42). Individuals classified as propylthiourea tasters perceive the bitterness of propylthiourea more intensely, have a higher density of fungiform taste papillae, and have more taste pores per taste bud than do nontasters (42–44). Bartoshuk (45, 46) reported a trimodal distribution of responses to propylthiourea, which she used to classify subjects as supertasters, tasters, or nontasters. Tasters were reported to be more sensitive to caffeine and quinine than nontasters (47, 48). Despite the large differences in genetically determined sensitivities to propylthiourea (or phenylthiocarbamide), propylthiourea status did not affect perceptions of the astringency of wine (37), acids (49), soymilk (40), or alum (50) or of the bitterness and astringency of phenolic compounds in water (14, 16, 31, 35). In contrast, Pickering et al (50) reported that supertasters and tasters were more sensitive than nontasters to the bitterness and astringency of red wine.

**Saliva**

Oral manipulation or even sipping of water can increase the salivary flow rate; however, dry crackers, acids, and astringents are the most potent elicitors of saliva flow. Unilateral monitoring of the salivary flow of the parotid salivary gland while subjects sipped wine and expectorated at 10 s revealed that the increase in flow rate was rapid but peaked at ~20 s and rapidly decreased until additional stimulation occurred (24). When subjects were partitioned into groups on the basis of their salivary flow rates and the data were analyzed separately, low-flow subjects perceived the maximal intensity of astringency later and rated it more intensely and for a longer time than did high-flow subjects, for both red wine
(37) and white wine (25) (Figure 5). However, conflicting results were observed in other studies, where astringency perception did not vary with salivary flow status (31, 35, 40).

When saliva flow is stimulated, saliva pH increases and the protein concentration decreases, although the total protein content remains fairly constant (51). Twenty-three percent of saliva proteins are basic proline-rich proteins (52), which have a strong affinity for binding polyphenols (53). HPLC profiles of proteins in human saliva revealed decreases in some proteins after ingestion of wine and grape seed tannin solutions, presumably as a result of tannin binding to these proteins. The appearance of a new protein peak 8 min after tasting was postulated to indicate the formation of a soluble protein-tannin complex (54). The oral sensation of astringency of polyphenolic compounds is thought to be linked to precipitation of these salivary proteins. It has been speculated that astringency is the friction perceived when oral lubrication is reduced after binding of astringent compounds to salivary proteins (35, 55, 56). Therefore, the lower astringency ratings for the high-flow subjects in Figure 5 may reflect their greater ability to restore oral lubrication, as a result of their greater volume of saliva.

**Effects of bitterness and astringency on preferences**

Taste preferences for sweet solutions and sweet products have been extensively studied, but there are far fewer studies addressing acceptance of bitterness or astringency. Bitter beverages (eg, beer, coffee, and tea) are not well accepted by children. Bitter beverages have been shown to be rejected because of their taste; beer and strong black coffee were rejected by 94% and 90% of American students (19–31 y), respectively (57). Astringency, like bitterness, is often perceived as a negative attribute, such as in soy products (58), dairy products (59), nuts (60), and juices (61). The astringency and bitterness of many vegetables and fruits containing phytonutrients are often cited as the reason for consumers rejecting the plant products, despite their known health benefits (62).

It is worth noting that consumers do not always describe bitter and astringent perceptions with the expected descriptors. Recently, Lesschaeve (I Lesschaeve, unpublished observations, 2003) studied the relationship between the consumer language used to express likes and dislikes and sensory descriptors of red wines. When consumers tended to like the wines, they did not use bitter as a descriptor; bitter was used to express dislike and tended to be associated with acid and astringent sensory characteristics, not bitterness. In the same study, consumers who liked astringent wines described them as having “a lot of character” or “a long aftertaste.”

When products are consumed under normal conditions, the sample is repeatedly ingested, which results in an increase in the intensity of both bitterness and astringency, as discussed above. Only one study has addressed the impact of this phenomenon on...
consumer liking (63). The temporal changes in bitterness, astringency, and overall aroma that occurred with repeated sips of wine influenced consumers’ liking. However, the hedonic responses varied among the consumer segments and wine styles. Among both frequent and less-frequent consumers of wine, some individuals liked the wine more as astringency increased, whereas others had a negative response to the increase in astringency.

Effects of exposure, social influences, and extrinsic factors on preferences

Preferences change with time, as noted for textural attributes of food by Szczesniak (64). Children show a developmental pattern of preferences for food textures, progressing from soft, smooth, unidimensional textures to firm, rough (astringent), complex textures. Acquisition of liking for innately disliked products is possible. With even short-term exposure to bitter foods, hedonic ratings increased (65, 66). In experiments conducted with children (67, 68) or with adults (69), liking for novel food products increased after “forced” exposures. Pliner (69) suggested that, with the repeated exposure, the subjects had overcome their neophobia, ie, fear or reluctance to ingest novel foods. Stein et al (66) reported that a positive liking shift appeared after 7 days of exposure to a bittersweet drink, which was speculated to have occurred through learned association of flavor with postigestive consequences. In a study of several novel foods, Mattes (65) found that liking of bitter and sour foods was more resistant to change than were hedonic ratings for sweet and salty items.

Modifying the bitterness and/or astringency of foods by adding masking agents or developing debittering processes can enhance palatability. Such processes involve teaming with flavor companies, which recommend first working with a base to mask off-notes and then accentuating desired flavors with the addition of actual flavors. Working with a base to cleanse the product of undesired qualities helps avoid the problem of “overflavoring” and allows the flavorist to select the most complementary flavors for the formula (70).

Overall acceptability is also influenced by extrinsic properties, such as health claims, price, appearance of the label, brand, and color of the product. Moreover, the hedonic response is affected by the consumer’s expectations for the product, which are based on factors such as previous experience, peer pressure, expert recommendations, and brand familiarity (71, 72).

Social factors may be the most potent means of enhancing liking among humans. If an adult demonstrates pleasure when consuming a food, then this positive response can influence the hedonic response of a child (73). For many drinks, such as coffee, tea, beer, aperitif, and wine, the positive value generally associated with the social context of consumption can be an important mechanism for learning to like the beverage, which might have been unpleasant initially.

CONCLUSIONS

Many phenolic compounds with important health benefits are characterized by bitterness and astringency, which are often perceived as aversive. The intensity of these sensations can be modified with additives, such sweeteners, or through modification of the concentrations or compositions of the polyphenols. Modifying the sensory properties may not be the only solution, because consumers very often like foods or beverages that are initially perceived as unpalatable. Learning to like astringent red wines may require repeated exposure and is enhanced by peer pressure and consumption under positive conditions.

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