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A Direct Comparison of the Taste of Electrical and Chemical Stimuli

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Abstract

Three multidimensional scaling studies were conducted to compare the taste qualities evoked from electrical and chemical stimulation, including ferrous sulfate as a typical "metallic" taste stimulus. Bipolar, anodal, and cathodal stimulation were delivered by 1.5- or 3-V batteries applied to the tongue. Solutions of chemical stimuli including prototypical tastes and binary mixtures were evaporated on small metal disks to provide tactile impressions similar to those of the battery stimuli and avoid any potential response biases induced by the subjects' knowledge of the form of the stimulus. Multidimensional unfolding was performed to place stimuli and verbal descriptors in common perceptual spaces. Bipolar, anodal, and cathodal stimuli were tested in separate experiments but generated very similar perceptual spaces and were differentiated from the chemical stimuli. Electrical stimuli were associated with descriptors, such as metallic, copper penny, and iron nail, regardless of the polarity of stimulation. Taste qualities evoked by electric stimuli may not be fully described by commonly used taste stimuli or their binary mixtures and appear most adequately described by a unique metallic taste.

Key words: electric taste, metallic taste, multidimensional scaling

Electrical stimulation to the tongue can be produced by bipolar, anodal, or cathodal current. Suprathreshold bipolar stimulation of the anterior tongue has produced metallic and/or sour taste qualities (Bujas et al. 1980; Lawless et al. 2005). There are reports of suprathreshold anodal stimulation tasting sour having a sour–metallic taste or both sour and metallic tastes (Bujas et al. 1974; Bujas and Mayer 1977; Bujas et al. 1980; Cardello 1981; Ajdukovic 1984, 1990), but stimulation of single papillae has also produced a salty taste (Cardello 1981). The reported qualities of cathodal stimulation have been more varied. The cathode has been described as producing bitter, bitter–sweet, metallic–sour–sweet, bitter–salty, and salty sensations (Bujas 1971; Bujas et al. 1974; Bujas and Mayer 1977). Electrical stimuli can also produce somatosensory sensations, such as prickling, burning, tingling, and a buzzing vibration (Bujas and Mayer 1977; Cardello 1981; Frank et al. 1986; Murphy et al. 1995). Ajdukovic (1984) found that "tactile" sensations may be more likely to be experienced with more intense electrical stimulation. Thus, the taste of electrical stimuli may be described by a combination of tactile sensations, the classical basic tastes, and metallic sensations.

Recent work has shown that the metallic tastes reported following rinses with ferrous sulfate are nearly eliminated by nasal occlusion, consistent with the proposal that these metallic "tastes" are in fact retronasally mediated olfactory perceptions (Hettinger et al. 1990). Given the large literature on metallic-smelling lipid oxidation products, it seems likely that these sensations arise from ferrous sulfate catalyzing a rapid lipid oxidation in the mouth (Lawless et al. 2004). In contrast, the metallic taste qualities of copper, copper and zinc bimetallic foils, and zinc sulfate and of electrical taste are all unaffected by nasal occlusion, indicating that some metallic taste reports are evoked by oral stimulation independent of any olfactory processing (Lawless et al. 2004, 2005). Thus, there are 2 mechanisms for evoking metallic taste, but whether these sensations are equivalent, or resemble mixtures of the common "basic" taste stimuli, is unclear.

Since the early work of Schiffman and Erickson (1971; Schiffman 1980), multidimensional scaling (MDS) has proven a useful tool for modeling the perceptual similarities and differences of diverse chemical stimuli. MDS and more broadly, multivariate techniques used for perceptual mapping have proven useful in understanding the properties of amino acids (Schiffman, Sennewald, and Gagnon 1981), terpene aroma materials (Lawless 1989), and lipid oxidation products (Macrae et al. 1990) as examples. Relevant to the current study, MDS has been used to show that many gustatory stimuli are differentiated from and not easily circumscribed by taste stimuli representing the traditional 4 basic tastes (Schiffman and Erickson 1971; Lim and Lawless 2005; Stevens et al. 2006). In other words, MDS studies often failed to duplicate or recover the simple tetrahedral model proposed by Henning, with many stimuli falling outside boundaries prescribed in Henning's model by prototypical taste stimuli, such as sucrose, salt, acid, and quinine. Recent multivariate studies of chemical stimuli including ferrous sulfate have also demonstrated that this stimulus, which often evokes metallic taste reports, will plot away from other simpler taste stimuli and outside the boundaries circumscribed by the common, classical taste stimuli (Lim and Lawless 2005; Yang and Lawless 2005; Stevens et al. 2006). However, these studies did not include any electrical stimuli, and thus, similarities and differences between the tastes of electrical and chemical stimuli were not determined.

In the version of MDS utilized in the present study, rectangular scaling or unfolding, participants provide estimates of the dissimilarities between the sensations produced by chemical stimuli and relevant attributes. A model is then created with Euclidian distances between points in the model reflecting the judged dissimilarities. Two important advantages of this method as employed here are first, that the judgments are made in the context of examples of tastants and second, that the distances between the sensations produced by stimuli of interest (electrical stimulation in the present study) and attributes and also between the stimuli of interest and exemplars of those attributes are modeled. For example, judgments are represented both of the similarity of the electrical sensations and the taste of NaCl and of the similarity of electrical sensations and the attribute ''salty.'' Utilization of the exemplars of tastes eliminates problems associated with the semantics of attributes.

In order to examine the similarities and differences of chemical and electrical taste, a stimulus that is similar to the electrode utilized in electrical taste stimulation in its tactile characteristics is needed to minimize perceptual differences due to tactile stimulation or due to subjects' inferring qualities based on knowledge of the form or origin of the stimulus, the so-called ''stimulus error'' (Titchener 1909). That is, subjects might presume any metallic-looking device to evoke metallic taste responses and therefore be biased by the visual appearance of the stimulus. To this end, in the present study, a chemical stimulus was coated onto a metal delivery device similar in area and form to the battery stimuli used previously (Lawless et al. 2005). Recent work comparing the battery device to unipolar anodal stimulation with the Rion electrogustometer showed that a 1.5-V battery would evoke a response equivalent to about 50 μA, the middle of the range used in clinical testing (McClure and Lawless 2007).

A second research question concerned the polarity of the electrical stimulation. Recent studies in our laboratories have employed a simple 1.5-V battery affixed to a plastic handle for stimulating different areas of the tongue (Lawless et al. 2005; McClure and Lawless 2007). This device makes primary contact with the tongue with the negative side, although there is a part of the positive pole that extends across the barrel of the battery and includes a small annular ring on the negative side. Thus, the stimulation with this device is necessarily bipolar, with (negative ion) current flowing across the tongue outward toward the positive annular ring. In contrast, most of the literature on electric taste has used unipolar stimulation with the circuit completed by some kind of grounding electrode on a different part of the body. One example is the Rion electrogustometer, which is popular in clinical testing and for which extensive normative data exist (Tomiyama et al. 1971; Tomita and Ikeda 2002). The Rion device provides anodal contact with the tongue and the circuit is completed by a grounding neck band that contains a gel pad. In order to compare the pattern of qualities evoked by bipolar stimulation to unipolar tongue contact, we modified the battery device to isolate either the anodal or cathodal pole from tongue contact and completed the circuit by a hand-held electrode of the opposite polarity.

The objectives of this study, then, were to compare the qualities evoked by electrical and chemical stimuli using MDS as an exploratory tool. A primary question was the degree to which electrical stimulation evoked metallic taste responses, about which there are substantial differences in the literature (McClure and Lawless 2007).

Comparisons were made to the qualities of bipolar, anodal, and cathodal electrical taste. Judgments of the relations between electrical taste, chemical taste, and common taste attributes were scaled by multidimensional unfolding.

Materials and methods

Participants

All participants were volunteers from a student population. They were in good health and reported having no respiratory or food allergies. A $5 honorarium was paid to each. The protocols were reviewed and approved by the Clark University Institutional Review Board.

For the bipolar condition, data were collected from 20 female and 6 male volunteers aged from 18 to 21 years; for the anodal condition, data were collected from 21 female and 11 male volunteers aged from 17 to 22 years; and for the cathodal condition, data were collected from 20 female and 5 male volunteers aged from 18 to 30 years.

The participants were screened for reliability of scaling by comparing their ratings of saltiness of the 2 samples of NaCl. In the bipolar condition, the distribution was bimodal; 4 of the female participants gave ratings of the 2 identical samples that differed by 47 or more units, whereas the remaining participants' ratings differed by less than 20 units of the 100 unit scale (mean absolute difference = 6.6). The 4 outliers' data were omitted from all analyses. For the remaining participants ($N = 22$), the mean ratings of saltiness for the 2 NaCl samples were 86.1 and 85.4. In the anodal condition, a comparison of saltiness ratings of the 2 samples of NaCl showed 5 female participants and 3 males gave ratings of the 2 identical samples that differed by 22 or more units. The data from those 8 participants were not analyzed nor those from a fourth male as he gave very low ratings for saltiness and bitterness for NaCl and QHCl, giving a final N = 23. For the remaining participants, the mean ratings of saltiness for the 2 NaCl samples were 88 and 89 units, with a mean absolute difference of 6.4. In the cathodal condition, 3 of the female participants gave ratings of the 2 identical samples that differed by 44 or more units, whereas the remaining participants' ratings differed by less than 20 units (mean absolute difference = 6.5) of the 100 unit scale. The 3 outliers' data were omitted from all analyses (final N = 22). For the remaining participants, the mean ratings of saltiness for the 2 NaCl samples were 91 and 92.

Chemical stimuli

For all 3 conditions, 9 chemical stimuli were utilized, 4 of which were mixtures. These were deposited in aqueous solutions to the center of #10 stainless steel washers (11 mm outside diameter) affixed to the end of 12-cm long plastic rods by epoxy cement. The solutions were then allowed to evaporate before the washers were applied to the tongue. The chemical stimuli and the amounts applied in solution are given in Table 1. Distilled water (Poland Spring) was the diluent. Concentrations were pilot tested to insure that the sensations evoked by the chemical stimuli were in a moderate intensity range and typical of their liquid counterparts.

Electrical stimuli

Bipolar stimulation

Following Lawless et al. (2005), electrical stimulation was provided by 1.5-V silver oxide and 3-V lithium batteries (diameters = 11.5 and 10.0 mm, respectively). These were attached to 12-cm long plastic rods by epoxy cement. A full description and diagram of this device as well as a functional comparison to the Rion electrogustometer can be found in McClure and Lawless (2007).

Anodal stimulation

Electrical stimulation was the same as for the bipolar condition, except that a wire was soldered to the cathode, connecting it electrically to a 10-cm long section of 16-mm diameter copper pipe that was held in the palm of participant's hand. Electrode jelly was utilized to facilitate conduction. For 3-V stimulation, a second 1.5 V battery was wired in series in the circuit. All the battery except the circular rear surface (anode) was covered by epoxy cement to chemically and electrically insulate it. The current flowing through the circuit was determined immediately after the make and before the break of contact for 14 trials, with 1-min intertrial intervals that included a water rinse of the mouth. The mean ± standard error (SE) currents were 146.6 ± 3.3 μA for 1.5 V and 465.4 ± 8.2 μA for 3 V.

Cathodal stimulation

Electrical stimulation was provided as for anodal stimulation, except the grounding wire was soldered to the anode and all the battery except the center electrode (cathode) was covered by epoxy cement. The mean ± SE currents were 89.9 ± 3.5 μA for 1.5 V and 204.7 ± 3.4 μA for 3 V.

Procedure

The 10-cm line scales with bipolar descriptors, listed in Table 2, were used for scaling the sensations' attributes. Sheets with

Table 1 Chemical stimuli and their plot symbols

Chemical	Amount (dry weight, mg)	Plot symbol
Aluminum ammonium sulfate	0.11	ALUM
Citric acid	0.50	CA
Ferrous sulfate heptahydrate	0.042	FeSO4
Monosodium glutamate	0.86	MSG
Sodium chloride	1.36	NaCl
Quinine hydrochloride	0.084	QHCl
Citric acid + quinine hydrochloride	0.23 + 0.043	CAQHCl
Citric acid + sodium chloride	0.25 + 0.76	CANaCl
Sodium chloride + quinine hydrochloride	0.76 + 0.047	NaQHCl

Table 2 Bipolar descriptors and their plot symbols for the attributes measured by line scales

Descriptor	Plot symbol
Dull–Sharp	Sharp
Not brothy–brothy	Brothy
No tingle–strong tingle	Tingle
Not copper penny–copper penny	Penny
Not metallic–metallic	Metallic
Not bitter–bitter	Bitter
Not iron nail–iron nail	Nail
Not salty–salty	Salty
No sting–strong sting	Sting
Not sweet–sweet	Sweet
Unpleasant–pleasant	Pleasant
Not dry–dry	Dry
Not chalky–chalky	Chalky
Not sour–sour	Sour

4 different random orders of attributes were used, and the sheets were randomly assigned to stimuli with the restriction that successive sequences could not be the same.

Bipolar condition

Volunteer participants gave informed consent and then were seated behind a screen for privacy at a table with a napkin, a water cup of distilled water for rinsing, beaker, mirror, pencil, and stack of 14 scaling sheets. A wastebasket for sample-cup disposal and an elevated spittoon, composed of a large funnel nested in an opaque glass jug, were on the floor. The experimenter was seated at a desk on the opposite side of the screen. The participant rinsed his or her mouth with distilled water. Then, for each trial, the experimenter handed a stimulus rod to the participant who then placed the treated washer or battery on the tip of the tongue for 1 s (using the mirror if necessary), mentally noted the sensations produced, and placed the rod in the beaker or if holding a battery returned it to the experimenter. The participant then indicated the extent to which each of the attributes described the sensations produced by the stimulus by marking the attribute scales. One or more distilled water rinses were then made until there were no residual sensations from the stimuli. A 60-s intertrial interval was imposed after the last rinse. The stimuli were presented in random order except that samples of sodium chloride, presented twice per subject to permit a check on reliability, were never presented on immediately successive trials. The distance of scale markings from the end of the line were recorded to the nearest millimeter, giving scores with a range of 0–100 scale units.

Anodal condition

The procedure was the same as for bipolar stimulation except that immediately before the testing began, a strip of electrode gel was put on the participant's right palm and the participant gripped the copper electrode. The trials were then given. When electrical stimuli were presented to the participant, the experimenter completed a connection between the anode and hand-held electrode, allowing current to flow when the participant applied the anode to the tongue.

Cathodal condition

The procedure was identical to that used for anodal stimulation except that the cathode was applied to the tongue.

Analysis

Ratings were submitted to rectangular MDS (multidimensional unfolding) by ALSCAL (SPSS, Version 14). This procedure produces a model of the relations between all pairs of stimuli, between stimuli and attributes, and between all pairs of attributes by placing points representing stimuli and attributes in *n*-dimensional space utilizing a best-fit algorithm. The R Statistics Package, SensoMineR (R Development Core Team), was used to analyze the correspondence of the output configurations by generating Rv coefficients to assess the overall correspondence (Husson and Lê 2006; Husson et al. 2006). An Rv coefficient greater than 0.7 is generally considered a good level of agreement (Cartier et al. 2006). Cluster analysis (Euclidean distance, average linkage) was performed on SYSTAT based on the coordinates obtained from MDS.

Results

Bipolar stimulation

Multidimensional unfolding gave initial solutions showing that the point representing the attribute "sweet" was an outlier, probably because there were no nominally sweet stimuli presented, and it disproportionately compressed the array of remaining points. The data were then analyzed with the sweet attribute omitted. A 3-dimensional solution produced a satisfactory model (S-stress = 0.110), which accounted for 98% of the variance of the scaled data.

The 3-dimensional model for bipolar stimuli is shown in Figure 1. Although this 3-dimensional plot gives a general representation of the model, it cannot unambiguously illustrate the relative distances between points, except when both points lie on the plane of the surface of the paper. The apparent distances between points in the plot depend on the distance of the points from that plane and the lines' angle from the plane. Accordingly, Euclidian distances between points representing the 2 electrical stimuli and attributes and between the electrical stimuli and other tastants are shown in Table 3. Distances between points for electrical stimuli and attributes are given in Table 4. For reference,

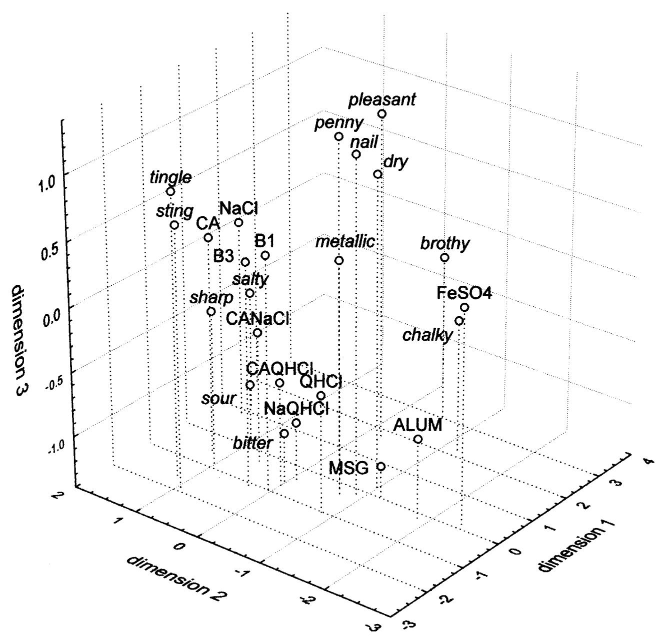

Figure 1 Three-dimensional model for bipolar stimulation.

the distances of the 2 NaCl stimuli were 0.68, for the citric acid (CA)/quinine mixture, and metallic were 1.29. Maximal separations were typified by the descriptor words "chalky" and "brothy" (distance from CA 3.7 and 4.0, respectively) which were poorly associated with any of the other stimuli or descriptors.

The attributes related to metallic tastes ("metallic" and "copper penny") were closely associated with electrical stimulation. The scaling shows close associations of the expected descriptor words with traditional salty, sour, and bitter tastants. However, the association of electrical stimuli with the taste of FeSO4 was relatively distant, which was closer to alum, an astringent compound (Yang and Lawless 2005). This general pattern was confirmed by a cluster analysis, showing an association of the battery stimuli with the terms metallic and copper penny and separate clusters for the taste mixtures and single basic tastes as shown in Figure 2.

Table 3 Distances of battery stimuli from chemical stimuli

	Bipolar		Anodal		Cathodal	
	1.5 V	3 V	1.5 V	3 V	1.5 V	3 V
Battery (other)	0.29	0.29	0.55	0.55	0.59	0.59
CA + QHCl	1.04	1.04	1.46	1.34	2.14	2.06
CA + NaCl	1.19	1.11	1.87	1.39	2.69	2.43
QHCl	1.27	1.41	2.25	2.19	1.85	1.90
CA	1.30	1.10	1.75	1.39	1.75	1.46
NaCl + QHCl	1.50	1.51	2.68	2.47	3.01	2.96
MSG	2.25	2.39	3.18	2.94	3.79	3.65
Alum	2.40	2.61	1.72	2.14	2.69	2.92
NaCl	2.48	2.40	3.23	2.91	3.37	3.37
FeSO4	2.68	2.95	2.46	2.80	2.58	2.96

Table 4 Distances of battery stimuli from attributes

	Bipolar		Anodal		Cathodal	
	1.5 V	3 V	1.5 V	3 V	1.5 V	3 V
Metallic	1.01	1.28	1.47	1.46	1.53	1.66
Sharp	1.16	0.92	1.69	1.21	2.24	1.80
Sting	1.28	1.06	1.67	1.23	1.64	1.06
Tingle	1.33	1.10	1.61	1.09	1.53	0.94
Copper penny	1.38	1.62	1.27	1.47	2.06	1.94
Iron nail	1.48	1.74	2.31	2.46	1.87	2.11
Bitter	1.50	1.48	1.79	1.57	2.45	2.31
Dry	1.72	1.98	1.58	1.63	2.25	2.41
Sour	1.97	1.87	1.84	1.35	2.55	2.11
Pleasant	2.86	3.01	2.60	2.70	2.58	2.66
Salty	2.87	2.79	3.35	3.05	3.68	3.94
Chalky	3.53	3.70	3.68	3.75	3.56	3.80
Brothy	4.11	4.24	4.03	4.03	3.71	3.79

Anodal stimulation

Multidimensional unfolding again showed the attribute sweet as an outlier, and it was omitted from the final analysis. For the 3-dimensional solution, which accounted for 98% of the variance in the scaled data, S-stress = 0.111. The distances found between points for electrical stimuli and tastants are shown in Table 3. Distances between points for electrical stimuli and attributes are given in Table 4.

Anodal stimulation produced sour, bitter, metallic, and tactile sensations. The third closest tastant association was alum, which was experienced as a metallic sensation; the distances between alum and FeSO4, copper penny, iron nail, and metallic ranged from 0.87 to 1.50, relatively small distances (the association of FeSO4 and copper penny was

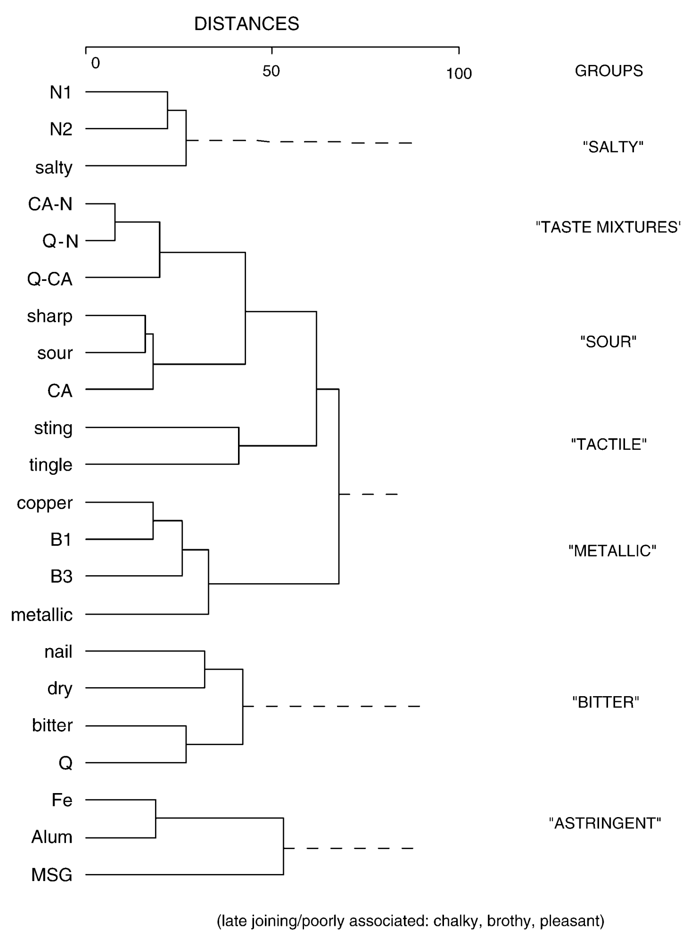

Figure 2 Cluster analysis, Euclidean distance, average linkage, based on the coordinates from Figure 1.

a distance of 1.54). Metallic attributes were the nearest attributes for the point representing 1.5-V anodal stimulation (Figures 3 and 4). Cluster analysis produced similar patterns to those seen in Figure 2.

Cathodal stimulation

Ratings were submitted to rectangular multidimensional unfolding with the sweet attribute omitted, as was done for bipolar and anodal stimulation. For the 3-dimensional solution, S-stress = 0.119, accounting for 98% of the variance of the scaled data. Distances between points for electrical stimuli and tastants are shown in Table 3. Distances between points for electrical stimuli and attributes are given in Table 4. Cluster analysis produced similar groupings as seen in Figure 2 for bipolar stimuli, with associations of the electrical stimuli with the term metallic. Distances of the electrical stimuli with all other stimuli and descriptor words are shown in Figures 3 and 4.

Comparison of polarity conditions

MDS configurations from bipolar, anodal, and cathodal stimulation were very similar, with both anodal and cathodal stimuli plotting in positions similar to the bipolar stimuli in Figure 1. Configurations were compared using the Rv coefficient (Robert and Escoffier 1976), a multivariate measure of correlation, which varies from 0 (no correspondence) to 1 (perfect correspondence). Rv coefficients were uniformly high, with Rv of 0.65 for the bipolar/cathode comparison, 0.77 for the bipolar/anode comparison, and 0.84 for the anode/cathode comparison. The correlation across the anodal and cathodal 1.5-V stimuli (from values in Table 3) was +0.88 and across the 3 V stimuli was +0.90 (rho of +0.77 and +0.94). Correlations among the bipolar, anodal, and cathodal stimuli from Table 3 ranged from +0.70 to +0.88. Comparing the verbal profiles from Table 4, similar high correlations were found, +0.84 to +0.94 ($P < 0.01$ for all correlations).

The associations between the sensations from cathodal stimulation and descriptors were similar to those for anodal stimulation. The shortest distances between points for electrical stimulation and tastants were for the modally sour and bitter substances CA and quinine (QHCl). However, the closest associations between the electrical stimulation and attributes were metallic and tactile qualities; bitter and sour descriptors were more distant.

The relations between anodal and cathodal stimulation by the 2 voltages and the tastants and attributes modeled by the scalings are shown in Figures 3 and 4. Points for tastants and attributes are plotted as a function of distances from the anodal and cathodal stimuli. These comparisons are valid because the equivalent scales were produced by ALSCAL and the total distances for both scalings were 696. Furthermore, points expected to be equidistant for the 2 scalings were

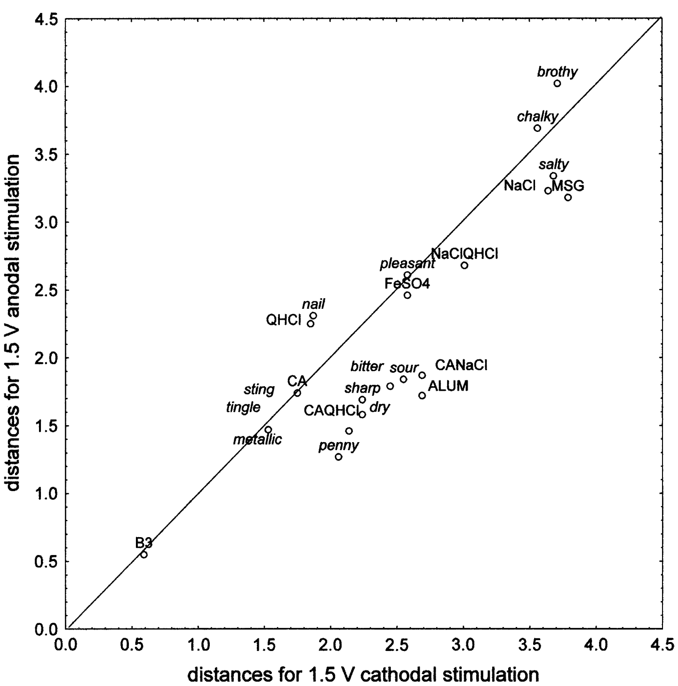

Figure 3 Distances between points for electrical stimulation and tastants and attributes for 1.5-V anodal and cathodal sources. Points to the right of the diagonal indicate the tastant or attribute describes anodal stimulation better than cathodal. Points to the left of the diagonal represent the opposite. A point's distance from the origin represents the degree of dissimilarity.

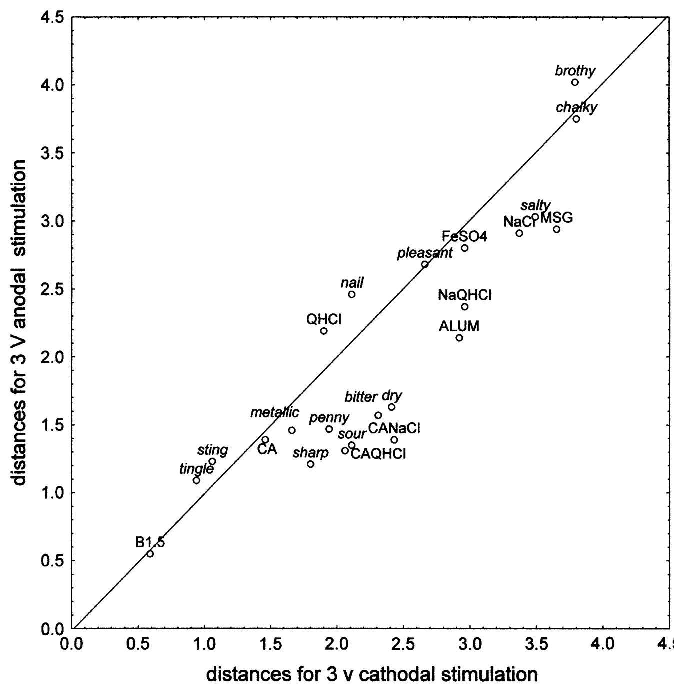

Figure 4 Distances between points for electrical stimulation and tastants and attributes for 3V anodal and cathodal sources. Points to the right of the diagonal indicate the tastant or attribute describes anodal stimulation better than cathodal. Points to the left of the diagonal represent the opposite. A point's distance from the origin represents the degree of dissimilarity.

equidistant, as seen for pleasant (distances of 2.61 and 2.58 for 1.5 V; 2.68 and 2.66 for 3 V) and chalky (distances of 3.69 and 3.56 for 1.5 V; 3.75 and 3.79 for 3 V), for example.

Tastants and attributes whose points are equally distant from the electrical stimulus would fall along the diagonal line. For example, the distances for CA were about the same for anodal and cathodal 1.5-v stimulation (1.74 and 1.75, respectively), and thus the point for CA falls on the diagonal. Points below and to the right of the line show that those tastants and attributes are less descriptive for cathodal stimulation than anodal, and points above and to the left of the line indicate tastants and attributes less descriptive of anodal stimulation than cathodal.

The points having the shortest distances from the electrical stimuli, and thus plotted closest to the plots' origins, were for metallic, sour-bitter, and sour tastants and descriptors. Points for bitter and bitter tastants were the next most associated with electrical stimulation. In general, those tastants and attributes described anodal stimulation better than they did cathodal as the points generally fell to the right of the diagonal.

Discussion

Rather than to compare the battery stimuli to liquid chemical stimuli, this study used a metal delivery system for chemical stimuli with a thermal/tactile imprint that was similar to the battery. This was done to avoid the stimulus error or any bias that might be introduced by the visually obvious metallic nature of the delivery device. In spite of the textural similarity of the delivery systems, the MDS configurations showed a clear differentiation of chemical and electrical stimuli, an association of the electrical stimuli with metallic taste words, and an association of the chemical stimuli with their expected taste labels (e.g., sour for CA).

Metallic tastes or flavors have been reported in foods (Hunzinger et al. 1929; Zacharias and Tuorila 1979; Borocz-Szabo 1980; Bodyfelt et al. 1988), in taste stimuli such as acesulfame-K (Schiffman et al. 1985) and in burning mouth syndrome (Grushka 1987). Metallic taste has also been reported as the quality of electrical taste (Bujas 1971). Descriptions of the taste qualities evoked by electrical stimulation have differed in the literature. Frank et al. (1986, p. 188) stated, "most people report the subjective experience of electrical taste to be a taste of well-defined quality even though it may not be fully described in terms of the four basic tastes." Tomita et al. (1986, p. 11) concluded from an analysis of area and quality from electrical stimulation that metallic taste was a unique quality "different from the four primary tastes." Other workers have only attempted to describe the sensations in terms of the 4 basic tastes and provide no mention whatsoever of metallic or other taste descriptors (e.g., Adjokovic 1984, 1990). In the Japanese clinical literature, the most common response adjective in a normal (control) population to anodal stimulation was metallic (Tomiyama et al. 1971). In a recent direct comparison, the taste qualities evoked were similar for both electrogustometer and battery devices. The modal response frequency occurred for the adjective metallic, with other common responses being sour, bitter, and pain (McClure and Lawless 2007). The similarity of the quality evoked by the bipolar stimulation with battery device and from the unipolar anodal stimulation is also the general pattern seen in this study using MDS.

The restriction of taste descriptor words in psychophysical studies, that is, to a few traditional options, has been a contentious issue for some time (O'Mahony and Thompson 1977). The frequency of choices of descriptor words in electric taste studies can be influenced by the options or descriptor lists that are provided (Murphy et al. 1995, McClure and Lawless 2007). Furthermore, the profiling of a stimulus in terms of some descriptor list does not necessarily imply that the actual sensation evoked was some analyzable combination of those qualities (Lawless 1999). For example, an orange color may be "profiled" in terms of its redness and yellowness using psychophysical intensity scales, but the perception is of a single color. In the present study to avoid semantically based errors and biases in description resulting from furnished descriptor lists, descriptors were provided in a context that included their exemplars. MDS was utilized for analysis as it has generally been considered a useful tool for characterizing the qualitative gradations among chemical stimuli (Schiffman, Reynolds, and Young 1981).

The older literature on electrical taste showed that the onset of anodal stimulation produced primarily sour, salty, or metallic sensations. The taste produced by the onset of cathodal stimulation was unclear but often described as bitter or bitter–sweet. The offset of anodal current did not produce a taste or a taste different than did onset, and the offset of cathodal current produced a sour taste (Bujas 1971). In the present study, participants were not asked to differentiate between sensations associated with onset and offset of the current. One reason was the compound nature of the offset of current as a stimulus. It is necessary that the onset of any stimulus precede its offset, and thus, any peripheral and central stimulation and sensations produced by onset will confound any stimulation produced by offset and affect those sensations that might be produced by it. Consequently, specification of the offset as a stimulus is difficult especially when the period of stimulation is as brief as 1 s, and generalizations about its effects difficult to make. Because metallic is not a usual characteristic of current offset, the characterization of electric taste as metallic found here is unlikely to be associated specifically with offset of the current.

The more intense 3-V stimulus evoked responses that are more similar to tactile (sting/tingle) sensations. This is consistent with the clinical literature showing that currents above 300 μA are needed to stimulate areas of the anterior tongue on the side ipsilateral to chorda tympani transection, thus recruiting only trigeminal afferent fibers (Krarup 1958; Bull 1965). In contrast, the electrogustometric threshold on the anterior tongue is about 8 μA in the Japanese literature and forms the reference point of 0 db on the electrogustometer calibration. The battery device, with its larger electrode surface (approximately 87 mm^2 as opposed to 20 mm^2 for the Rion probe), may well be recruiting trigeminal fibers at the higher level of 3 V stimuli. The influence of area was emphasized by Adjukovic (1990), who argued that it was current density rather than intensity that was the key measure of stimulus strength.

With both bipolar and unipolar stimulation, the current flows between anode and cathode through saliva and tissue. In the former condition, the path is short and does not involve deeper tissue to any great extent. In the latter, the current flows between the lingual locus of stimulation to the electrode in the hand. This would involve current flow through nonlingual material, but there is no reason to believe that this would produce the sensations experienced as electrical taste. Although the paths differ in length, involvement of saliva and lingual tissue is common to both. Because similar sensations were found under the bipolar and unipolar conditions, this result is consistent with the electrolytic chemical hypothesis (Bujas 1971) but is not a critical test of it.

In conclusion, this study provides a direct comparison of electrical to taste stimuli using MDS. This was achieved with a chemical stimulus delivery system similar in visual appearance and tactile impression to the electrical taste stimuli in order to minimize potential biases (i.e., the stimulus error). Electrical stimuli were most closely associated with descriptors related to metallic taste. Ferrous sulfate was less so, perhaps due to its astringency (Yang and Lawless 2005) and/or the inability of this type of delivery system to evoke a metallic retronasal smell from ferrous sulfate. Contact with a large surface area appears necessary to initiate the lipid oxidation reaction needed for retronasal metallic smell. Electrical stimuli produced sensations only modestly related to sour (and perhaps bitter) taste and were perceptually distinct from the taste mixtures studied here. Whether electric taste operates by mechanisms distinct from those of chemical stimuli remains unclear. Future psychophysical studies might examine the overlap in mechanisms of chemical and electrical stimulation by techniques such as cross adaptation.

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References

Ajdukovic D. 1984. The relationship between electrode areas and sensory qualities in electrical human tongue stimulation. Acta Otolaryngol. 98: 153–157.

Ajdukovic D. 1990. Electrical taste stimulus: current intensity or current density. Chem Senses. 15:341–347.

Bodyfelt FW, Tobias J, Trout GM. 1988. Sensory evaluation of dairy products. New York: Van Norstrand/AVI.

Borocz-Szabo M. 1980. The influence of iron contamination on the sensory properties of liquid foods. Acta Aliment. 9:341–356.

Bujas Z. 1971. Electrical taste. In: Beidler LM, editor. Handbook of sensory physiology, Vol. 4, chemical senses, Part 2: Taste. Berlin (Germany): Springer. p. 180–199.

Bujas Z, Dogan S, Mayer D, Szabo S, Vukosav Z. 1980. Electrical stimulation of human tongue receptors and summated cortical potentials. Acta Inst Psychol Univ Zagrabiensis. 87:11–21.

Bujas Z, Mayer D. 1977. Sensory effects of continuous and iterative electrical stimulation of the tongue. Acta Inst Psychol Univ Zagrabiensis. 82: 35–50.

Bujas Z, Szabo S, Kovacic M, Rohacek A. 1974. Adaptation effects on evoked electrical taste. Percept Psychophys. 15:210–214.

Bull TR. 1965. Taste and the chorda tympani. J Laryngol Otol. 79:479–493.

Cardello AV. 1981. Comparison of taste qualities elicited by tactile, electrical, and chemical stimulation of single human taste papillae. Percept Psychophys. 29:163–169.

Cartier R, Rytz A, Lecomte A, Poblete F, Krystlik J, Belin E, Martin N. 2006. Sorting procedure as an alternative to a product sensory map. Food Qual Prefer. 17:562–571.

Frank ME, Hettinger TP, Herness MS, Pfaffmann C. 1986. Evaluation of taste function by electrogustometry. In: Meiselman HL, Rivlin RS, editors. Clinical measurement of taste and smell. New York: Macmillan. p. 180–199.

Grushka M. 1987. Clinical features of burning mouth syndrome. Oral Surg Oral Med Oral Pathol. 63:30–36.

Hettinger TP, Meyers WE, Frank ME. 1990. Role of olfaction in perception of non-traditional 'taste' stimuli. Chem Senses. 15:755–760.

Hunzinger OF, Cordes WA, Nissen BH. 1929. Metals in dairy equipment. Metallic corrosion in milk products and its effect on flavor. J Dairy Sci. 12: 140–181.

Husson F, Lê S. 2006. SensoMineR: sensory data analysis with R. R package version 1.05 [Internet]. [cited 2008 January 3]. Available from: http://sensominer.free.fr, http://www.agrocampus-rennes.fr/math/SensoMineR.

Husson F, Lê S, Mazet J. 2006. FactoMineR: factor analysis and data mining with R. R package version 1.00 [Internet]. [cited 2008 January 3]. Available from: http://factominer.free.fr, http://www.agrocampus-rennes.fr/math/.

Krarup B. 1958. Electro-gustometery: a method for clinical taste examinations. Acta Otolaryngol (Stockh). 49:294–305.

Lawless HT. 1989. Exploration of fragrance categories and ambiguous odors using multidimensional scaling and cluster analysis. Chem Senses. 14:349–360.

Lawless HT. 1999. Descriptive analysis of complex odors: reality, model or illusion? Food Qual Prefer. 10:325–332.

Lawless HT, Schlake S, Smythe J, Lim J, Yang H, Chapman K. 2004. Metallic taste and retronasal smell. Chem Senses. 29:25–33.

Lawless HT, Stevens DA, Chapman KW, Kurtz A. 2005. Metallic taste from electrical and chemical stimulation. Chem Senses. 30:185–194.

Lim J, Lawless HT. 2005. Qualitative differences of divalent salts: multidimensional scaling and cluster analysis. Chem Senses. 30:185–194.

Macrae AW, Howgate P, Geelhoed EN. 1990. Assessing the similarity of odours by sorting and by triadic comparison. Chem Senses. 15:661–669.

McClure ST, Lawless HT. 2007. A comparison of two electric taste stimulation devices, metallic taste responses and lateralization of taste. Physiol Behav. 92:658–664.

Murphy C, Quinonez C, Nordin S. 1995. Reliability and validity of electrogustometry and its application to young and elderly persons. Chem Senses. 20:499–503.

O'Mahony M, Thompson B. 1977. Taste quality descriptions: can the subject's response be affected by mentioning taste words in the instructions? Chem Senses. 2:283–298.

Robert P, Escoffier Y. 1976. A unifying tool for linear multivariate statistical methods: the 'RV' coefficient. Appl Stat. 25:257–265.

Schiffman SS. 1980. Taste quality and neural coding: implications from psychophysics and neurophysiology. Physiol Behav. 69:147–159.

Schiffman SS, Crofton VA, Becker TG. 1985. Sensory evaluations of soft drinks with various sweeteners. Physiol Behav. 34:369–377.

Schiffman SS, Erickson RP. 1971. A psychophysical model for gustatory quality. Physiol Behav. 7:617–633.

Schiffman SS, Reynolds L, Young F. 1981. Introduction to multidimensional scaling. New York: Academic Press.

Schiffmann SS, Sennewald K, Gagnon J. 1981. Comparison of taste qualities and thresholds of D- and L-amino acids. Physiol Behav. 27: 51–99.

Stevens DA, Smith RF, Lawless HT. 2006. Multidimensional scaling of ferrous sulfate and basic tastes. Physiol Behav. 87:272–279.

Titchener EB. 1909. A text-book of psychology. Vol. 1. New York: Macmillian.

Tomita H, Ikeda M. 2002. Clinical use of electrogustometry: strengths and limitations. Acta Otolaryngol Suppl. 546:27–38.

Tomita H, Ikeda M, Okuda Y. 1986. Basis and practice of clinical taste examinations. Auris Nasus Larynx. 13(Suppl):S1–S15.

Tomiyama H, Tomita H, Okuda Y. 1971. Normal value of the electric taste. Jpn J Otol (Tokyo). 74:58–65.

Yang HH, Lawless HT. 2005. Descriptive analysis of divalent salts. J Sens Stud. 20:97–113.

Zacharias R, Tuorila H. 1979. Der Reiz- und Erkennungsschwellenwert für Metallverbindungen in verscheidenen Prüfmedien. [Taste thresholds for metallic salts in different media]. Lebens Wiss Technol. 12:36–40.

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