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Metallic Taste from Electrical and Chemical Stimulation

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Abstract

A series of three experiments investigated the nature of metallic taste reports after stimulation with solutions of metal salts and after stimulation with metals and electric currents. To stimulate with electricity, a device was fabricated consisting of a small battery affixed to a plastic handle with the anode side exposed for placement on the tongue or oral tissues. Intensity of taste from metals and batteries was dependent upon the voltage and was more robust in areas dense in fungiform papillae. Metallic taste was reported from stimulation with ferrous sulfate solutions, from metals and from electric stimuli. However, reports of metallic taste were more frequent when the word ‘metallic’ was presented embedded in a list of choices, as opposed to simple free-choice labeling. Intensity decreased for ferrous sulfate when the nose was occluded, consistent with a decrease in retronasal smell, as previously reported. Intensity of taste evoked by copper metal, bimetallic stimuli (zinc/copper) or small batteries (1.5-3 V) was not affected by nasal occlusion. This difference suggests two distinct mechanisms for evocation of metallic taste reports, one dependent upon retronasal smell and a second mediated by oral chemoreceptors.

Keywords

electric taste; electrogustometry; ferrous sulfate; metallic taste

Introduction

Metallic tastes or flavors have been reported in foods (Hunzinger, 1929; Zacharias and Tuorila, 1979; Borocz-Szabo, 1980; Bodyfelt et al., 1988), in sweeteners such as acesulfam-K (Schiffman *et al.*, 1985), after stimulation with calcium and magnesium salts (Lawless *et al.*, 2003), from anodal electrical stimulation of the tongue (Frank *et al.*, 1986; Frank and Smith, 1991), after section of the chorda tympani (Bull, 1965), in direct stimulation of the human chorda tympani (Eliasson and Gisselsson, 1954; Frenckner and Preber, 1954), as a phantom taste disturbance during pregnancy (Nordin *et al.*, 2004) and in burning mouth syndrome (Grushka, 1987). Following oral exposure to solutions of ferrous sulfate ($FeSO_4$), a metallic sensation develops (Schiffmann, 2000; Lawless *et al.*, 2004). Two common reference standards for metallic taste in applied sensory panel training have been dilute ferrous sulfate solutions and a clean copper penny (Civille and Lyons, 1996). Although metallic sensations have only rarely been considered one of the basic or primary taste qualities (Bartoshuk, 1978), the frequency of reports of this sensation warrants further investigation as to its nature, possible mechanisms, and the conditions under which it is evoked.

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Odors in the mouth can cause reports of tastes, a situation sometimes called gustatory referral. This is primarily due to passage of volatiles into the nasal passages from the mouth through the nasopharynx, called retronasal smell. Retronasal smell, and thus referred gustatory sensations, are effectively eliminated by closing the nose during stimulus sampling (Murphy and Cain, 1980) or by injecting a pure airstream through the external nares, preventing retronasal transport (Mozell *et al.*, 1969). The sensation from ferrous sulfate solutions is primarily a retronasally perceived sensation as it is effectively decreased by nasal occlusion (Hettinger *et al.*, 1990; Lawless *et al.*, 2004). However, a retronasal effect seems unlikely for metal stimuli such as a copper penny (nasal occlusion has no apparent effect). Whether the metallic sensation from electrical stimulation is affected by nasal closure is unknown.

Bujas (1971, p. 180), in reviewing the history of electrical stimulation of the tongue, hinted at the perceptual similarity of electrical and ferrous sulfate stimulation as follows (italics added): ‘In 1754, a quarter of a century before Galvani's experiments with frog's legs, Sulzer had described a way in which taste was induced by two different, interconnected metals touched by the tongue (lead-silver)...He described the taste produced *as being like that of ferro-sulphate.*’

The experiments conducted below were designed to look at the similarities and differences of stimulation with metals, electrical stimulation, and solutions of divalent salts and ferrous sulfate in particular. Whether nasal occlusion would affect the sensations from metals and electrical stimulation in a similar manner to the reduction seen with $FeSO_4$ was of interest. Such a similarity would imply generation of a retronasally perceived volatile. On the other hand, if sensations from metallic and electrical stimulation are unaffected by nasal closure, the possibility arises that a second mechanism for metallic taste may act via gustatory receptors, as recently argued by Schiffmann (2000). A related question concerns under what conditions subjects report ‘metallic’ sensations. Metallic sensations are not part of everyday taste experience from foods, although they can arise from packaging transfer and lipid oxidation as well as direct exposure to metal wrapping foils, containers and utensils. A methodological issue concerned whether subjects would choose the word ‘metallic’ when it was offered as a choice on a questionnaire as opposed to freely choosing that word when no descriptors were suggested.

A sequence of three exploratory studies was conducted. The first study examined whether metallic taste reports could be generated by copper stimuli, as suggested in the food science literature, and/or by electrical stimulation. An electrical stimulus consisting of a small battery mounted on a handle was fabricated to facilitate stimulation of different oral areas. Four areas of the mouth were explored to see whether metallic taste reports could be evoked from non-gustatory areas. The second study expanded on the first by including a nasal occlusion condition to see whether metallic taste reports from electrical stimulation might involve a retronasal smell component as previously found for ferrous sulfate rinses. A third study re-examined this possibility using both within-and between-subject designs and changed the process of choosing descriptors from a cued multiple choice format to a free-recall uncued format.

Materials and methods (general)

Subjects

All subjects were recruited from the Cornell University campus or the surrounding area (Tompkins County, NY). Participants received no prior training and were unaware of the purpose of the study. Each participant granted his/her consent at the beginning of the study, and received a token incentive at the conclusion of the session. All were non-smokers, in good health with no reported problems in taste or smell function. The protocol was approved by the University Committee on Human Subjects.

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Stimuli

Solid stimuli were affixed to 25 cm long plastic handles with a drop of polyacrylate glue (Duro Quick-gel No-run Superglue). In experiment 1, each subject received his/her own set of stimuli to minimize microbial transmission. In experiments 2 and 3, solid stimuli were sanitized between participants in bleach (5% sodium hypochorite for 30 s) and ethanol. Solutions were prepared in deionized water (16.5-18 MΩ resistance, with 0.2 μm filter). Solutions were given as 10 ml samples in 30 ml plastic cups at room temperature (~20°C) in experiments 1 and 3. In experiment 2 solutions were 'painted' on the edge of the extended anterior tongue with a cotton swab for a distance of ~2 cm bilaterally. Spring water was provided for rinsing and cups were available for expectoration. Rinsing and expectoration were monitored carefully to insure compliance.

Procedure

In each experiment, a single test session was conducted in the sensory evaluation facility in the Deparment of Food Science, Cornell University. Informed consent was given, questions answered, then magnitude estimation was practiced using lengths of lines and sizes of circles with different colored segments. Answers were checked to ensure understanding of the use of ratio judgements and fractionation of overall intensities into subqualities. Total intensity was judged using magnitude estimation relative to a 0.10 M NaCl standard, which was assigned the value of 10. Before stimulation with the solid stimuli, subjects again rinsed and tasted the 0.10 M NaCl standard which they were reminded was a value of 10. Prior to stimulation, all batteries were checked with a voltmeter (Sears Craftsman Digital Multimeter # 82015) and found to be within the range of 1.50-1.60 V for the batteries labeled 1.5 V and within the range of 2.97-3.11 V for the batteries labeled 3 V. Sessions were conducted on a one-to-one basis (over a ~25 min period) to ensure proper compliance with procedures, except for experiment 3 group B, who were tested in groups in tasting booths in the sensory evaluation laboratory. In experiments 2 and 3, one complete set of liquid and solid stimuli were tested while subjects wore Spirometrics Spiro Nose clips (Spiro No. 2110; Spirometrics Medical Equipment, Grey, ME) and another complete set were tested with the nose clips off. Conditions were counterbalanced and orders of stimuli were randomized. Participants received two samples per minute, with ~30 s for rinsing between samples. Intensity data were analyzed by repeated measures analysis of variance using SYSTAT 5. Frequency counts were made of descriptors and changes as a function of nasal occlusion analyzed by the nonparametric McNemar test for changes (Siegel, 1956, pp. 63-67).

Experiment 1: Metallic and electrical stimulation in different oral areas

The first experiment investigated whether electrical stimulation produces a sensation similar in intensity, quality and relative responsiveness across oral locations to stimulation with metals. Anodal electrical stimulation has been variously described as salty, sour and metallic (Bujas, 1971; Frank *et al.*, 1986; Frank and Smith, 1991). We included salt, acid and salt-acid mixtures to see whether the stimulation with metals and electrical current would generate similar or different quality reports. Because of the use of copper pennies as reference standards for metallic taste in applied sensory evaluation of foods, they were included as well as a copper penny with the zinc core exposed. Preliminary work had shown that a much stronger metallic sensation was achieved with the bimetallic zinc-exposed penny. As a simple method for stimulating with electrical current, a stimulus was devised consisting of a small battery affixed to a plastic handle, to facilitate stimulation of different oral areas.

Methods

Subjects—Ten subjects (ages 18-52 years, five female) participated.

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Stimuli—Solutions were 0.001, 0.003 and 0.01 M citric acid, 0.03, 0.10 and 0.30 M NaCl, and a mixture containing 0.003 M citric acid and 0.10 M NaCl. A deionized water stimulus was also presented. Three solid stimuli were affixed to handles as noted above: a 1.5 V battery (1 cm disk, anode side exposed), a 2 cm copper disk (a US penny) and a 2 cm disk, half zinc and half copper. The bimetallic disks were produced by filing the copper coating off post-1981 US pennies to expose the zinc core. Before stimulation, all stimuli were briefly burnished with 400 grit emery paper (to remove any oxidized coating and leave a fresh metal surface exposed), soaked for 10 s in isopropyl alcohol and then air dried.

Procedure—*Liquid stimuli.* Subjects rinsed with spring water before each liquid sample. All samples were tasted for 2-3 s and expectorated. Overall taste intensity was rated and then broken down into subqualities of sweet, sour, salty, bitter or ‘other’. The following choices for ‘other’ were listed in front of the subject: brothy, soapy, alkaline, metallic, rusty, astringency, fishy, tingle, irritating, spicy. They were instructed to use any words they felt appropriate. Two replications of the eight stimuli were presented, each in a different random order. The standard was given before the first, fifth, and ninth stimuli. Subjects ate at least one half of an unsalted cracker and rested for one minute between replicates.

Solid stimuli. Four sites were stimulated on the right and left sides for 2 s: the anterior dorsal tongue near the edge, the medial tongue ~2 cm posterior to the tip, the inside of the upper lip and buccal surface approximately opposite the first molars. All four sites were stimulated with one type of stimulus before the next one was tested. Subjects rinsed between stimulus changes. Subjects were tested with their eyes closed so they could not see the type of stimulus, but were told what part of the tongue, lip or cheek was about to be touched. Both sides were touched and then responses given verbally for each side and recorded by the experimenter. Subjects were asked not to report sensations of touch, cold or warmth but that anything else should be reported. Before tongue stimulation, subjects were asked to extend their tongue. Before lip stimulation, subjects were asked to wet their upper lip and purse it slightly to allow access to the inside surface. Subjects were asked to open their mouths wide before cheek stimulation. Dental contact was avoided and subjects were asked to report the sensation they experienced at the time of stimulus placement and not anything that followed after removal.

Results

There were no main effects of side (laterality) nor any interactions involving laterality and so data were averaged across the two sides (all $Ps > 0.24$). Figure 1 shows the mean rated intensities of the three stimuli on the four oral loci. There was a site by stimulus interaction [$F(6,54) = 4.90$, $P < 0.01$]. Anterior tongue stimulation with the 1.5 V battery evoked the highest intensity rating, about equal to the reference standard of 0.1 M NaCl. The anterior tongue was the most sensitive area followed by the medial tongue. Responses from the inside of the upper lip were very low (median of zero). Responses from the cheek were highly variable, with most subjects reporting little or no sensation but with a few responsive individuals. The battery was the most effective stimulus, followed by the zinc/copper stimulus [main effect of stimulus, $F(2,18) = 8.29$, $P < 0.01$]. Quality judgements of the stimuli showed that ‘metallic’ was the most frequent descriptor on the anterior and medial tongue, and ‘no sensation’ was the most common descriptor for the lip and cheek. Frequencies are shown in Table 1. Frequencies do not always sum to 10 because some subjects chose not to respond (5/120 presentations) and some subjects responded with more than one descriptor (2/120 presentations).

For the liquid stimuli, subjects tracked increases in concentration with increases in rated intensity in the expected manner. The mean ± SD intensity of the 0.1 M NaCl was 11.1 ± 0.91, which was not significantly different from the reference standard value of 10. Subjects choose the descriptor ‘salty’ for NaCl almost exclusively, and ‘sour’ was the most frequent descriptor

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for citric acid. Mixture suppression was evident in that salty and sour tastes reported for the mixture fell below the intensities of their unmixed components. Of 241 total descriptors chosen (mean of 24 per subject), 63% of responses were either salty, sour or both. Other frequently chosen descriptors were bitter (15%) and astringent (7%), mostly assigned to citric acid or the acid/salt mixture.

Discussion

Responses to anodal electrical stimulation of the tongue have been described as sour, salty and metallic. Our results confirm that weak electrical stimulation of the tongue can induce metallic taste reports. Thus there appear to be at least two mechanisms for eliciting metallic taste. One is through a retronasal smell sensation induced by rinses with iron salts such as $FeSO_4$ (Hettinger *et al.*, 1990; Lawless, *et al.*, 2004), which is effectively reduced and sometimes completely eliminated by nasal occlusion. However, a second kind of metallic sensation can be elicited in the mouth from exposure to copper, zinc or weak electric currents. Like many other sensory phenomena (sweetness being one example) there are multiple stimuli and multiple modalities that can elicit a common word from untrained observers. Whether nasal occlusion would have any effect on electrically evoked metallic taste is unclear and was addressed in experiment 2.

Our panel used the metallic descriptor with high frequency, and very few responses to the solid stimuli evoked taste words such as salty and sour. This may have been due to the procedure, in which the liquid salt and acid stimuli were presented first. Having tasted a number of items for which salty and sour descriptors seemed quite applicable, they may have perceived sufficient qualitative difference in the metal stimuli to seek another descriptor word. The context within which a stimulus is judged can have profound effects on its perceived intensity and quality (Lawless *et al.*, 1991).

The areas of greater response were those with fungiform papillae. The anterior dorsal tongue was more effective than the medial tongue surface, another parallel to fungiform density. This parallel has been reported in the literature (Føns, 1970; Salata *et al.*, 1991; Miller *et al.*, 2002). It is one of the sources of evidence that electric current stimulates gustatory pathways rather than trigeminal nerves (Frank *et al.*, 1986), although this evidence is not conclusive because of the presence of numerous trigeminal afferents in fungiform papillae (Farbman and Hellekant, 1978). However, electrical stimulation is widely considered to be mediated by gustatory pathways because thresholds dramatically increase on the front of the tongue when the chorda tympani is severed (Frank *et al.*, 1986; Tomita and Ikeda, 2002).

Experiment 2: Comparison of metal foils, electric current and taste solutions with and without nasal occlusion

Experiment 2 examined the responses to liquid stimuli, including metal salts, as well as common taste stimuli. The metal stimuli in experiment 1 were replaced with stimuli constructed of high purity metal foils. Although the pennies were cleaned and chosen to be of limited circulation, there was some possibility that they had been exposed to oils from the skin from handling and that some residual oxidation products were present. A 1.5 V and a 3.0 V battery were used to examine the effect of increasing electrical stimulation level, and a Teflon control stimulus of approximately the same size was included as a baseline. Liquid stimuli were swabbed on the edges of the extended anterior tongue to provide an area of stimulation similar to that touched by the solid stimuli. Subjects were tested with the nose open and closed. It was hypothesized that nasal occlusion would decrease the perceived intensity of sensations from ferrous sulfate solutions but not those from the solid metals or electrical stimuli.

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Methods

Subjects—Twenty-three subjects who did not participate in the previous study (ages 22-55 years, six males) participated.

Stimuli—Metal salts were represented by 0.003 M $FeSO_4$, 0.001 M $CuSO_4$ and 0.001 M $ZnSO_4$ solutions, tastes were represented by 0.3 M NaCl, 0.3 M sucrose, 0.02 M citric acid, 0.0001 M quinine-HCl and 10 g/l monosodium glutamate, and astringency was represented by 1 g/l aluminum ammonium sulfate ('Alum'); deionized water was used as a control. Solid stimuli were a Teflon disk (1.9 cm in diameter), a 1.5 V silver oxide battery, a 3.0 V lithium battery, a 2 cm copper square with rounded corners made from reagent grade 0.25 mm copper foil (Aldrich) and a similar copper square with a 1 cm square of reagent grade zinc foil affixed to the center with superglue.

Procedure—For the liquid stimuli, participants responded on a sheet comprising a grid with five columns, with headings as follows: Order, Code, Intensity (How strong?), What word would you pick to best describe this taste? Any other words? For the solid stimuli, participants responded verbally and the experimenter recorded the data on a similar data grid. Words could be chosen from a descriptor list composed of three columns with the following alternatives: no taste, sweet, savory, metallic, bitter, irritating, salty, astringent, soapy, sour, rusty, peppery, fishy, tingle, sharp, spicy, broth-like, lemony. Subjects were instructed to use any words they felt appropriate, whether or not they were on the list of choices.

For the solid stimuli, participants closed their eyes and extended their tongues. The experimenter placed the solid stimuli on the participant's tongue on the left then the right side (or left then right, alternated randomly between participants); 2 mm from the edge. The experimenter questioned participants on the intensity rating relative to the standard, on words that described the sensation and recorded responses. Solid stimuli were presented in random order and half of the stimuli were presented with the nose occluded.

Results

Figure 2 shows the mean intensity ratings of the solid stimuli. The 3 V battery evoked the strongest response, followed by the 1.5 V battery, the bimetallic squares, the copper-only and Teflon disk [$F(4,88) = 32.8$, $P < 0.001$]. There was no effect of nasal occlusion nor any interaction with nasal condition. For the liquid stimuli, there was an interaction of nose condition with stimulus [$F(9,198) = 2.82$, $P < 0.01$]. The ferrous sulfate solution was less intense with the nose closed (sign test, $P < 0.001$) and a small difference was also seen for sucrose ($P < 0.05$).

Descriptor frequencies for the solid stimuli are shown in Table 2. 'Metallic' sensations were recorded for the metal stimuli and their frequency increased with intensity. The 3 V battery evoked multiple sensations including those that might be associated with more tactile or trigeminal irritation (tingle and sharp/irritating). The majority of subjects responded with 'no sensation' reports to the Teflon disk. For the $FeSO_4$ solution, the frequencies of metallic descriptors were 13/23 with the nose open and only 2/23 with the nose closed, while 'no taste' responses were 3/23 with the nose open and 14/23 with the nose closed. In other words, the modal descriptor shifted from metallic with the nose open to no taste with the nose occluded (McNemar test for changes, $P = 0.004$). The modal choices for the classical taste stimuli were associated with their traditional qualities (sweet for sucrose, salty for NaCl, etc.), and no significant change was seen as a function of nasal occlusion.

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Discussion

Sensations from the copper and copper-zinc foils resembled those from stimulation with the anodal side of the batteries, except that they were less potent and somewhat less distinct in terms of evoked quality. This is perhaps not surprising as the bimetallic foil is capable of producing a small electrical current. To examine this possibility, ~2 ml of human saliva was placed on one of the bimetallic foil stimulus. A potential of 550 mV was recorded. Thus the bimetallic foil stimulus and the zinc-copper interface on the penny in experiment 1 are essentially weaker versions of the battery. This parallel could be tested using a clinical electrogustometer.

In contrast to the effects seen with $FeSO_4$ solutions after nasal closure—a decrease in intensity and decreased frequency of reports of metallic sensations—no such changes were seen with the electrical stimuli. Intensity was not altered and the frequency of quality reports was not changed in any substantial way. This implies a different mechanism for the perception of metallic sensations from electric current as opposed to solutions of ferrous sulfate. Retronasal smell does not play a part in electric taste, supporting the possibility of a true gustatory sensation.

Sensations from the stimuli painted on the anterior tongue edges were not very intense in this study. This raises the question of whether any different pattern might be seen with whole-mouth rinses as used previously (Lawless *et al.*, 2004), which could give a stronger and clearer impression. This issue is addressed below in experiment 3. Another issue is the extent to which providing a list of potential taste words (albeit embedded in a number of distractor words) might have influenced a higher level of reports of 'metallic' as opposed to what subjects would generate spontaneously. Shiffman (2000) reported that metallic sensations were virtually the sole response to threshold solutions of $FeSO_4$. In contrast, Murphy *et al.* (1995) found a lower frequency of metallic reports to electrical stimuli, and also found that restriction of responses to specific categories could change the frequency of qualities reported.

Experiment 3: Metallic taste reports without cues and comparison of nasal occlusion effects

There were two main objectives of experiment 3. The first was to re-examine the frequency of metallic taste reports in a free-choice situation as opposed to choosing word options from a predetermined list. The second was to re-examine whether the decrement in metallic taste reports with nasal occlusion was specific to stimulation with $FeSO_4$ solutions and conversely, not seen with electrical stimulation. To increase the strength and clarity of the sensation from $FeSO_4$, a sip-and-spit procedure was used as opposed to swabbing the anterior tongue edges. In the first group tested, only ~1/3 of the subjects chose to use the word 'metallic' for a weak level of $FeSO_4$. However, the low intensity of the stimulus leaves the possibility open that higher concentrations would more readily evoke metallic taste reports. Therefore a larger second group was also tested in order to see if a higher concentration level affected the frequency of response.

Methods

Subjects—Two groups of subjects participated. Group A consisted of 26 subjects who did not participate in the previous study (ages 19-56 years, 15 female). Group B consisted of 52 additional subjects (ages 18-65 years, 29 male).

Stimuli—For group A, solutions were 0.3 mM $FeSO_4$, 0.32 M NaCl, 0.32 M sucrose, 0.02 M citric acid, 0.001 M quinine-HCl and deionized water. Solid stimuli were a Teflon disk (1.9

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cm in diameter), a 1.5 V silver oxide battery and a 3.0 V lithium battery. For group B, solutions were 0.3 mM $FeSO_4$, 3.0 mM $FeSO_4$, 0.32 M NaCl and deionized water.

Procedure—For the liquid stimuli, participants responded on a sheet comprising a grid with columns for intensity ratings and descriptive words, as in experiment 2. For the solid stimuli, participants responded verbally and the experimenter recorded the data on a similar data grid. For group B, testing proceeded in isolated test booths. Data were collected using a computer-aided data collection system, Compusense® *five* release 4.6 (Compusense Inc., Guelph, ON, Canada).

Results

Solid stimuli—Figure 3 shows the mean ratings for the solid stimuli, the $FeSO_4$ solution and water for group A and the four liquid stimuli for group B, averaged across replicates. The 3 V battery was once again a more effective stimulus than the 1.5 V battery and the Teflon disk evoked little or no response [stimulus $F(2,50) = 98.8$, $P < 0.001$]. There was a small interaction of nose condition by replicate [$F(1,25) = 5.98$, $P < 0.05$], with the mean rating higher on repetition 2 in the closed condition than with the nose open; no such difference was observed on the first replicate. There was no main effect of nose condition nor an interaction of nose condition with stimulus. The descriptors chosen for the solid stimuli are shown in Table 3. In the free choice situation, less than half the subjects choose the metallic descriptor, in both groups. Frequency of choice of the 'metallic' descriptor did not change as a function of nasal occlusion.

Liquid stimuli—For group A, nasal occlusion reduced the mean rating of $FeSO_4$ [$t(20) = 2.24$, $P < 0.05$]. Data from five subjects who gave zero ratings to $FeSO_4$ with the nose open were omitted. For group B, mean intensities of both solutions of $FeSO_4$ decreased with the nose closed, and the NaCl and water controls were unaffected [interaction of nose condition by stimulus, $F(3,153) = 8.36$, $P < 0.001$]. The decrease in rated intensity for $FeSO_4$ when the nose was closed was accompanied by a shift from metallic taste responses to 'no taste'. Figure 4 shows the decrease in metallic descriptor choices when the nose was occluded (McNemar test for changes, $P < 0.01$ in all three cases for $FeSO_4$). There was no corresponding shift for water. Modal responses for the traditional tastants were as expected, salty for NaCl, sweet for sucrose, sour for citric acid and bitter for quinine. No change in intensity or descriptor frequency was seen as a function of nasal occlusion for these stimuli. Compared with experiment 2, in which 13/26 people responded 'metallic' to $FeSO_4$ with the nose open, there were 8/26 for 0.3 mM group A, 14/52 for 0.3 mM group B and 16/52 for 3.0 mM group B, a significant decrement in the uncued versus cued condition (binomial tests, $P < 0.05$).

Discussion

Nasal occlusion had no effect on intensity judgements from electrical stimulation at the voltage levels tested here. In contrast, judgements of the intensity of the $FeSO_4$ solutions, but not other tastants, decreased when the nose was closed. 'Metallic' descriptors were reported under uncued conditions, i.e. without being presented with a list of choices. However, reports of metallic tastes from the electrical stimulation were somewhat lower in these uncued condition with less than half reporting that choice in experiment 3 as compared with more than half the subjects in experiments 1 and 2. A similar decrement was seen for the $FeSO_4$ solutions, with less than half reporting metallic taste in experiment 3 with the nose open as opposed to more than half in experiment 2 in which choices were offered.

The Teflon disk provided an adequate control stimulus showing few reports of any taste-related sensations following stimulation. Of course, the ideal control stimulus for electrical stimulation would have been a depleted battery, but watch batteries are designed to be long-lasting and are

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difficult to deplete. Some reports of saltiness were probably due to deposition of sodium chloride. During the sterilization with bleach (5% sodium hypochlorite), the batteries caused a visible bubbling, due to degradation of the sodium hypochorite to sodium chloride and generation of O_2 gas. Future researchers are cautioned against this method of sterilization.

General discussion

The metallic impressions from $FeSO_4$ solutions are reduced or eliminated by nasal closure and those from electric stimulation are not. In spite of Sulzer's observation, over 250 years ago, that the sensation from bimetallic stimulation resembled that of ‘ferro-sulphate’, our results show differences in mechanisms for the perception of metallic sensations from these two kinds of stimuli. Stimulation with a 1.5 V battery and with a 10 ml sipped solution of 3 mM ferrous sulfate both evoke a metallic response near the intensity of a 0.1 M NaCl solution's saltiness. Changes (or lack thereof) in intensity were paralleled by and illuminated by the qualitative reports. Nasal closure almost always results in a decrease in metallic sensations reported after stimulation with $FeSO_4$ (except when it is weak or below a person's threshold) and a shift to increased frequency of reports such as ‘no sensation’. This shift in qualitative reports was not seen with electrical stimulation as a function of nasal closure.

Electrical stimulation is widely accepted to occur via activation of taste receptors, whereas the reduction of metallic ‘taste’ after nasal occlusion suggests a major component from retronasal olfaction (Hettinger *et al.*, 1990; Lawless *et al.*, 2004). To our knowledge, no one has directly compared electrical tongue stimulation with and without the nose closed, perhaps due to the common assumption that electric stimulation of the tongue produces a true gustatory phenomenon. The assumption is reasonable in that section of the chorda tympani causes loss of sensation to both chemical and electrical stimulation (Frank *et al.*, 1986; Tomita and Ikeda, 2002). It was suggested that the somatosensory versus gustatory contribution might be clarified by examining the effects of capsaicin desensitization on metallic taste. However, capsaicin applications can knock down taste responses such as bitter as well (Karrer and Bartoshuk, 1995), so this approach is not completely airtight. One might also be tempted to interpret the lack of response from the lip and cheek and robust response from the tongue to implicate gustatory receptors. A positive result from the non-gustatory areas is one source of evidence that astringency is at least partially a somatosensory phenomenon (Breslin *et al.*, 1993). However, the converse effect is not conclusive. Responses from fungiform papillae might still involve trigeminal afferents (Farbman and Hellekant, 1978), but ones with a higher threshold than those on the lip or cheek. It would be of interest to examine whether metallic reports can be evoked from electrical tongue stimulation in patients with unilateral trigeminal transection but intact chorda tympani.

Qualitative reports clearly can be affected by the format of the questions (Murphy *et al.*, 1995). A higher frequency of reporting metallic taste occurs when it is present on the list of choices than when subjects are required to describe tastes with no suggestions present. Synonyms and metal-related words such as ‘rusty’ were sometimes evoked. Even though we embedded the word metallic in a list of taste words and distractor words, its presence on the list could have been suggestive. It is possible that some persons do not normally think of metallic sensations as an appropriate response in a taste experiment. Others may have limited experience with metals in the mouth. Perceptually, the evocation of the word metallic would seem to arise from reference to previous experience. People can experience metallic oral sensations from dental procedures, from metal eating utensils, from accidental tastings of foils, wrappers or packaging, or from other oral encounters with metal objects. Still, it is noteworthy that subjects who are given choices including common taste words, and even exposure to tastes in experiments 1 and 2, chose a metallic descriptor at least some of the time.

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Solutions of $FeSO_4$ have little or no odor of their own outside the mouth (Lawless *et al.*, 2004), i.e. they are not effective orthonasal stimuli at the concentrations which evoke a strong retronasal smell. $FeSO_4$ may catalyze a rapid lipid oxidation in the mouth, creating metallic-smelling compounds such as trans-4,5-epoxy-decenal, (*Z*)-1,5-octadien-3-one and 1-octene-3-one (Guth and Grosch, 1990). These compounds are reported as metallic smelling in the food literature in gas chromatography sniff port analyses and they are extremely potent odors, with thresholds below 1 p.p.b. for epoxydecenal (Buettner and Schieberle, 2001).

Almost every chemical placed in the mouth has multiple sensory effects. The notion of a monogustatory tastant is illusory. Divalent salts such as the sulfates and chlorides of Fe, Ca, Zn and Cu produce multiple effects in the mouth, including metallic tastes, bitterness and astringency (Keast, 2003; Lawless *et al.*, 2004). Conversely, diverse stimuli may evoke a common description. The question remains why Sulzer in 1754 and our subjects in 2004 perceive some similarity in these two mechanistically different kinds of stimuli and apply the same word. It is possible that metallic gustatory sensations and metallic olfactory sensations occur simultaneously from some experiences. Thus an association could be formed, as is thought to be the case between sweet tastes and sweet aromatics (Stevenson *et al.*, 1995). An analogy can be made to the simultaneous experiences of sugar sweetness and aromatic carmelization products of sugars in baked goods and confections. These coincident sensations lead to the application of the same word (sweet) to experiences in both taste and smell.

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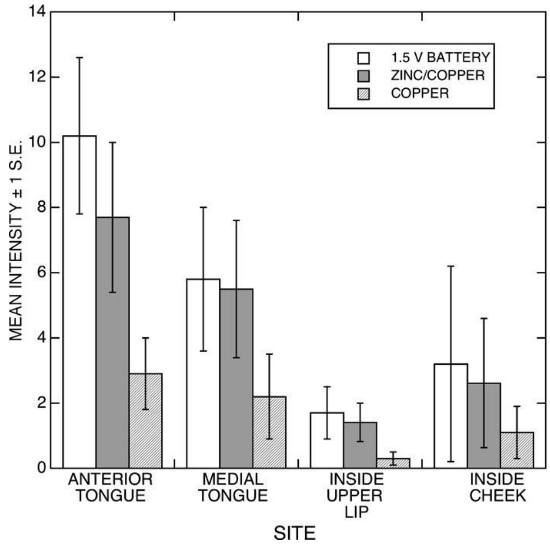

Figure 1.
Perceived intensity of the battery, zinc-copper and copper stimuli as a function of site of stimulation.

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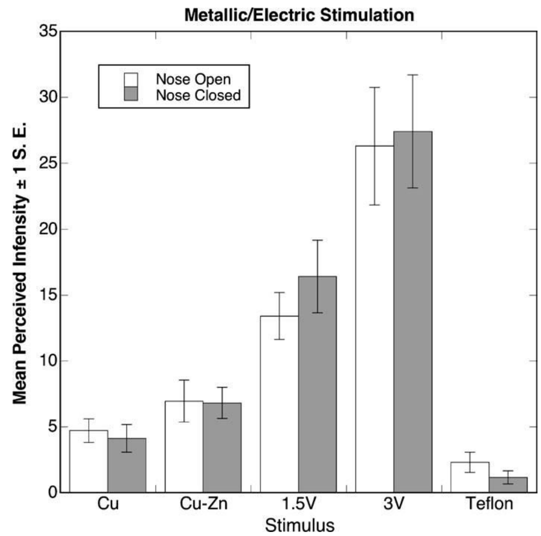

Figure 2.
Perceived intensity of solid stimuli in experiment 2, with and without nasal occlusion.

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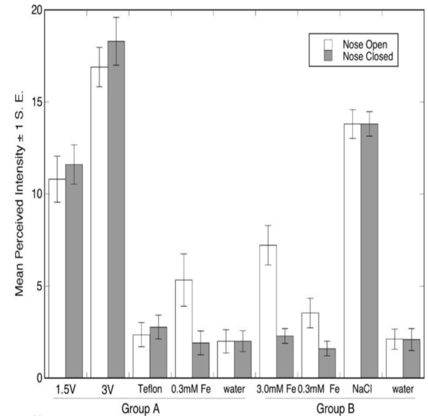

Figure 3.
Perceived intensity as a function of nasal occlusion for the solid stimuli, $FeSO_4$ solutions and water, in experiment 3.

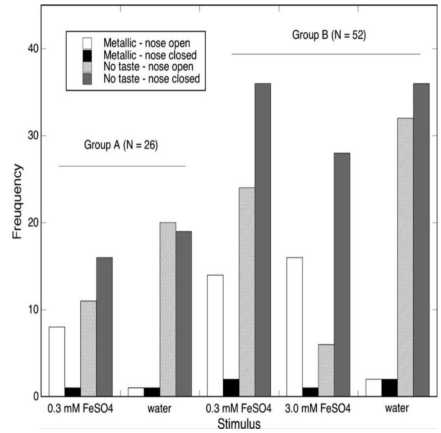

Figure 4.

Frequency of reports of metallic sensations versus ‘no taste’ or ‘water’ for $FeSO_4$ solutions and water in experiment 3 showing changes as a function of nasal occlusion for $FeSO_4$ solutions.

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Table 1

Descriptors chosen for experiment 1

	Metallic	Other	No sensation
Anterior tongue			
Battery	6	2	1
Zinc penny	7	4	1
Copper only	5	3	1
Medial tongue			
Battery	4	4	2
Zinc penny	6	4	3
Copper only	2	1	6
Inside upper lip			
Battery	0	4	5
Zinc penny	2	2	6
Copper only	0	1	9
Cheek			
Battery	0	2	8
Zinc penny	1	1	7
Copper only	1	1	8

Table 2

Descriptors chosen for solid stimuli for experiment 2

Stimulus	Metallic	Electric	Tingle	Sharp/ irritating	Salty	Sour	Other	No sensation
Copper strip								
Nose open	8	0	1	1	2	0	3	9
Nose closed	6	0	0	0	4	0	7	5
Copper/ zinc strip								
Nose open	10	0	2	1	3	3	6	5
Nose closed	8	0	3	3	5	1	6	5
1.5 V battery								
Nose open	16	2	6	4	2	3	10	0
Nose closed	13	1	5	3	3	4	5	0
3 V battery								
Nose open	14	2	5	7	1	3	9	0
Nose closed	9	5	6	5	0	8	11	0
Teflon disk								
Nose open	1	0	0	0	2	0	3	18
Nose closed	0	0	0	0	2	0	1	20

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Table 3

Descriptors chosen for solid stimuli for experiment 3, group A

	Metallic	Electric	Tingle	Sharp/ irritating	Salty	Sour	Bitter	No sensation
1.5 V battery								
Nose open	12	1	3	0	4	5	5	4
Nose closed	9	0	4	0	6	6	7	4
3 V battery								
Nose open	12	2	4	2	5	11	7	3
Nose closed	11	3	6	1	3	6	6	2
Teflon disk								
Nose open	2	0	0	0	6	0	3	22
Nose closed	1	1	0	0	8	0	1	18