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Electrotactile stimulation on the tongue: intensity perception, discrimination and cross-modality estimation

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Abstract

Due to its high sensitivity and conductivity, electrotactile stimulation (ETS) on the tongue has proven to be a useful and technically convenient tool to substitute and/or augment sensory capabilities. However, most of its applications have only provided spatial attributes and little is known about (a) the ability of the tongue's sensory system to process electrical stimuli of varying magnitudes and (b) how modulation of ETS intensity affects subjects' ability to decode stimulus intensity. We addressed these questions by quantifying: (1) the magnitude of the dynamic range (DR; maximal comfortable intensity/perception threshold) and its sensitivity to prolonged exposure; (2) subjects' ability to perceive intensity changes; and (3) subjects' ability to associate intensity with angular excursions of a protractor's handle. We found that the average DR (17 dB) was generally large in comparison with other tactile loci and of a relatively constant magnitude among subjects, even after prolonged exposure, despite a slight but significant upward drift ($P < 0.001$). Additionally, our results showed that as stimulus intensity increased, subjects' ability to discriminate ETS stimuli of different intensities improved ($P < 0.05$) while estimation accuracy, in general, slightly decreased (increasing underestimation). These results suggest that higher ETS intensity may increase recruitment of rapidly adapting mechanoreceptor fibers, as these are specialized for coding stimulus differences rather than absolute intensities. Furthermore, our study revealed that the tongue's sensory system can effectively convey electrical stimuli despite minimal practice and when information transfer is limited by memory and DR drift.

Keywords

Dynamic range; electrocutaneous; sensory substitution; sensory augmentation; psychophysics; human-machine interface

Introduction

Electrical stimulation on body surfaces that transmit touch information, i.e., electrotactile stimulation (ETS), can be used to activate the afferents below the stimulated surface and thus lead to perception (Bobich et al. 2007; Higashiyama and Rollman 1991; Kaczmarek and Haase

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2003; Kaczmarek et al. 2000; Kajimoto et al. 2004; Menia and Van Doren 1994; Tashiro and Higashiyama 1981; Warren et al. 2008). Two of the most commonly used applications of ETS to elicit stimuli above the perceptual threshold are *sensory substitution* and *augmentation*. With sensory substitution, ETS is delivered to provide sensory information of sensation that is mildly or completely impaired (Bach-y-Rita and Kercel 2003; Szeto and Riso 1990; Tyler et al. 2003). In sensory augmentation, ETS is used to enhance the response of an intact sensory system, such as to determine orientation in the dark or provide tactile sensation for tele-manipulation (Monkman et al. 2003; Tang and Beebe 2006).

The amount and reliability of transmitted information, comfort of stimulation and power consumption are all important criteria underlying the choice of stimulus location and other performance parameters (Kaczmarek and Bach-y-Rita 1995). The most studied body areas as targets for ETS include the abdomen, fingertip, forehead (Kaczmarek and Bach-y-Rita 1995) and more recently the lips (Liu and Tang 2005) and the tongue (Bach-y-Rita and Tyler 2000).

ETS on the tongue has been shown to have advantages relative to other tactile areas (e.g., fingertip) due to its higher conductivity and sensitivity. The tongue's higher conductivity results from its thinner cutaneous layer relative to the skin of other body areas as well as the presence of saliva, both of which provide a consistent, low-resistance electrotactile interface. High tongue sensitivity is attributable to densely distributed mechanoreceptive innervations (Trulsson and Essick 1997) and large somatosensory cortical representation (Picard and Olivier 1983). Although human fingertip has commonly been targeted because of its high sensitivity to mechanical stimulation (Weinstein 1968), stimulus pattern perception through ETS on the tongue is comparable to that resulting from the fingertip (Bach-y-Rita et al. 1998; Kaczmarek et al. 1997). Furthermore, the tongue is characterized by higher spatial resolution than the fingertip for both mechanical (Vanboven and Johnson 1994) and electrical stimuli (fingertip, Kaczmarek and Bach-y-Rita 1995; tongue, Maeyama and Plattig 1989).

Several studies have shown that biofeedback through tongue ETS can provide spatial information (Droessler et al. 2001; Tang and Beebe 2006), assist in image perception and cause cross-modality plasticity in the congenitally blind (Pitito et al. 2005), and improve motor output in postural tasks in both healthy and neurologically impaired individuals (briefly reviewed in Vuillerme et al. 2008 and Danilov et al. 2007).

Although these studies demonstrate feasibility and applicability of ETS on the tongue, most of this work focused on providing information using spatial attributes, e.g., stimulating different areas of the tongue to code for movement directions. Tongue ETS applications can be significantly extended to coding information by using stimulus intensity and frequency. However, very little is known about (a) the ability of the tongue's sensory system to process electrical stimuli of varying magnitudes and (b) how modulation of ETS intensity affects subjects' ability to decode stimulus intensity.

Our study was designed to evaluate the properties of the tongue's intensity coding (no taste perception), thus inferring the properties of the tongue's sensitivity to electrical stimulation. We assessed the usable ETS ranges (*dynamic range*) from perception threshold to maximum level without discomfort and quantified their changes after prolonged exposure to ETS. Furthermore, we quantified the sensitivity to perceived intensity changes as a measure of sensitivity of ETS on the tongue (*just noticeable differences*). Lastly, we assessed subjects' ability to match ETS intensity with the angular excursion of a protractor's handle (*cross-modality intensity matching*).

Materials and Methods

Eight healthy subjects (4 males and 4 females; ages 21-34) participated in one experimental session that lasted up to 3 hours. All subjects completed a health inquiry questionnaire and gave informed consent. The health inquiry was used to exclude subjects with conditions such as contagious diseases (e.g., HIV, Tuberculosis, Hepatitis, Herpes Simplex), mouth/tongue injuries (e.g., open wounds, abrasions, or surgery/dental work in the previous 3 months in the oral cavity), neurological disorders (numbness on the tongue, poor circulation, impaired sensitivity, inability to keep tongue in one spot over a period of time, etc.), or ingestion of substances (e.g., alcohol, pain killers, caffeine) within the 12 hours prior to testing that might affect performance and/or perception of the electrotactile stimuli. All subjects interested in participating in the study were included. The experimental procedures were approved by the Institutional Review Board at Arizona State University and were in accordance with the declaration of Helsinki.

Experimental protocols

We used three protocols: (1) 'Dynamic Range' to determine dynamic range (DR^1) and determine if it changes over long exposure to ETS, (2) 'Just Noticeable Differences' (JND) to quantify subjects' abilities to differentiate intensities within their DR, and (3) 'Cross-Modality Intensity Matching' (CMM) to quantify subjects' abilities to estimate these intensities.

In all protocols, subjects sat comfortably in front of a monitor that displayed instructions, accompanied by auditory cues, for each protocol (Figure 1A). Subjects were required to place the previously disinfected flexible gold-plated electrode array on the anterior-mid-section of the dorsal surface of the tongue. The tongue was electrically stimulated through a 6×8 electrode sub-array of the entire electrode array (6×12; Figure 1C), which allowed stimulation of a more medial region of the tongue, characterized to be more sensitive (Pleasanton 1970). The position of the array with respect to the tongue was kept constant by asking subjects to touch with the tip of their tongue the border of a plastic landmark attached to the array strip (Figure 1C) and by lightly holding the strip with their lips and teeth with their mouth closed. To ensure effective and constant transmission of ETS, we instructed subjects to gently press the array with their tongues against their palate to maintain the same pressure. The electrode strip was connected to the electrotactile stimulation unit (Figure 1A, B). Stimulation parameters are described in Appendix B.

After the DR protocol, the JND and CMM protocols were performed in a counterbalanced order, i.e., half of the subjects performed JND followed by CMM, the remaining subjects performed the reverse. To minimize fatigue, subjects were given rest periods of at least 5 minutes between protocols. We performed 2 to 9 practice trials for all protocols to let subjects familiarize themselves with each task.

Dynamic range protocol

We used this protocol to obtain the perception threshold (THR) and maximal stimulation without discomfort (MAX) levels used to determine the DR (ratio of MAX to THR). Note that THR was always determined before MAX using the ascending no/yes, 1/1 rule (one up/one down) staircase method with fixed step sizes (see criteria for method parameters in Appendix A). Subjects pressed the ENTER key to start a set of trials and waited 1 s before beginning the first trial. In each trial, subjects received an auditory signal and a message cueing the arrival

¹There are two ways to quantify DR: 1) stimulus DR - ratio of the physical MAX and THR values; and 2) perceived magnitude estimation of only the MAX level, since THR is perceived in a similar manner (magnitude-based DR; Kaczmarek et al. 1992). Although the latter is a better psychophysical measure because it does not co-vary with waveform manipulations, we used the stimulus DR (that we simply referred to as DR) as we were interested in perception at subdivision levels of the DR.

of the upcoming electrical stimulus. The stimulus was delivered to the subject's tongue for 0.5 s after which the subject was prompted (auditory cue and on-screen message) with the question “Do you feel it?” (for THR) or “Is it too strong?” (for MAX). Subjects answered by pressing ‘y’ (yes) or ‘n’ (no) on the keyboard. The trial ended when the subject pressed ENTER to input the response. Subjects were required to answer as quickly as possible to minimize the use of memory. A 1 s inter-trial delay preceded the next trial.

The voltage amplitude of the first trial was 50% of the average of 5 THR or MAX voltage measures previously obtained with the method of adjustment (see Appendix A). From the second trial onwards, the voltage was increased a step-up size each time subjects did not feel the stimulus or when they felt it was not too strong (THR or MAX determination, respectively). Likewise, the voltage was decreased a step-down size each time subjects felt it or felt it was too strong. The iterations stopped when the voltage step reversed direction 7 times. The THR or MAX voltage level was obtained from the average of the voltages presented at the trials where all but the first reversal occurred (note: last point included although not technically a reversal).

Subjects rested at least 2 min between sets of trials to minimize fatigue. We measured THR before MAX voltages as strong electrical exposure may produce some adaptation (Kaczmarek 2000) and thus require larger voltage levels to produce a perceived intensity level.

The DR at the beginning of the experimental session (staircase method) was divided into 9 equally-spaced voltages to obtain psychophysical measures evenly distributed along the DR (percentages of DR: from 0% (equivalent to THR) to 100% (equivalent to MAX) at 12.5% increments). These voltages were used as references for the JND and CMM protocols. After obtaining JND and CMM measures, we ran the DR protocol again to obtain a second set of THR and MAX voltages. This set was compared to the initial estimated DR to assess possible changes resulting from long exposure to ETS.

Just noticeable differences protocol

This protocol was used to determine the upper and lower difference thresholds of 9 reference voltage levels equally-spaced within the DR (see above). Difference threshold, ΔV , represents the magnitude of intensity change from a reference voltage that can be perceived as different, which is also a measure of discrimination variability (Gescheider 1985; Figure 2).

The *upper* and *lower* ΔV are the difference thresholds above and below the reference voltage (ΔV_u and ΔV_l , respectively). These ΔV s were obtained using a temporal 2-alternative-forced-choice (2-AC with “no difference” option; 2 up/1 down rule; Braun et al. 2004; Gridgeman 1959) ascending staircase method with fixed step sizes (see Appendix A). The temporal domain, where stimuli were presented at different times, was chosen to limit the stimulation of potentially different receptive characteristics at different tongue areas (spatial domain, Essick et al. 2003). The “no difference” response is an unusual but effective way to reduce the protocol's time, while obtaining statistically similar values with better power (Braun et al. 2004; Gridgeman 1959).

A trial consisted of sequentially obtaining one ΔV_l and one ΔV_u (Figure 2A). The ΔV_l and ΔV_u of each of the 9 reference voltages were obtained in 9 trials presented in random order. Each ΔV was obtained by running a set of sub-trials. In each sub-trial, subjects were stimulated with the reference voltage (gray bars in Figure 2A) and a voltage that was changed according to the subjects' response (‘adjusted voltage’; white bars in Figure 2A). Both reference and adjusted stimuli were cued (auditory) and delivered in random order for 0.3 s, each with an inter-stimulus delay of 0.2 s. Subjects were then prompted with the question “Which stimulus

felt stronger?" to be answered '0' ("I could not determine which was stronger" or "they felt the same"), '1' ("The first stimulus felt stronger"), or '2' ("The second stimulus felt stronger").

The sub-trial was completed when the subject entered the answer and the next sub-trial started 1 s later. The voltage amplitude of the first sub-trial for ΔV_l search was lower than the reference voltage and increased a step-up size when the answer was correct 2 (1 before 1st reversal) times in a row and decreased a step-down size if it was incorrect or zero. Step-ups made reference and adjusted voltage intensities closer and step-downs made them further apart. The procedures for ΔV_u search were the reciprocal. The iterations for both ΔV searches stopped when the voltage step reversed direction 8 times (Figure 2B). Once the two subsets of trials for both ΔV_l and ΔV_u searches were completed, subjects waited 10 s before performing the next trial with a different reference voltage. The voltage levels used to calculate the ΔV s were obtained from the average of the voltages presented at the trials where all but the first reversal for each ΔV search occurred (circles Figure 2B). Each ΔV was calculated as absolute value of the difference between the reference voltage and the voltage obtained for the set of sub-trials when searching for the corresponding ΔV . Step sizes and initial adjustable voltages were determined based on preliminary measures of ΔV_l and ΔV_u obtained with the method of adjustment (see Appendix A for details).

Cross-modality intensity matching protocol

We used this protocol to determine subjects' ability to match each of the 9 reference voltages to the angular excursion of a handle attached to a protractor (Figure 1A). We obtained 5 responses for each reference voltage presented in sets of 9 trials (with the 9 reference voltages). Before each set of trials, subjects were allowed to freely sense the stimulus intensity by moving the protractor's handle within the shaded area of the protractor, which represented the subjects' DRs (Figure 1A). In each trial, subjects received the reference voltage for 1 s. After the stimulation was over, subjects adjusted the protractor's handle using their hand from its initial position (0°; see Figure 1A) to a position within the shaded area corresponding to the perceived intensity relative to their DR. As a control, subjects were also instructed to leave the protractor's handle in the initial position (0°; left most) or to the maximal position (180°; right most) if they either could not feel the reference stimulation intensity or if they felt it was stronger than the MAX level (as chosen in the DR protocol), respectively.

The trial ended when subjects pressed ENTER to input the value, similar to the dynamic range protocol. Subjects then turned the handle back to the initial position and waited 10 s. Subjects rested at least 2 min between sets of trials to minimize fatigue.

Statistical analyses

We found that larger voltages (MAX vs. THR) were associated with significantly larger within-subject variability (Levene's test of homogeneity, $P < 0.001$). We corrected this problem (i.e., homogeneous variance of perceptual estimates across stimulus levels; $P > 0.05$) by transforming the data from Volts to decibels (dB) using the following formula:

$$\text{Voltage}_{\text{dB}} = 20 \log (\text{Voltage delivered} / \text{Voltage reference level}) \quad (1)$$

where, the voltage delivered was THR or MAX, and the Voltage reference level was arbitrarily chosen to be the same as the minimum voltage deliverable by the device (100 mV; see Appendix B). To convert DR voltage to dB (DR_{dB}), we transformed the values as follows:

$$DR_{dB} = 20 \log (MAX/THR) \quad (2)$$

To obtain the difference threshold for the JND data, we used the ratio of voltages that included the average of ΔV_u and ΔV_l (ΔV_{mn}) and the reference voltage, V , as follows:

$$\Delta V_{dB} = 20 \log ((V + \Delta V_{mn})/V) \\ \text{where } \Delta V_{mn} = (\Delta V_u + \Delta V_l)/2. \quad (3)$$

For the CMM responses we used the ratio of the average of the responses for each reference voltage and the minimum value of the protractor's range that represented THR:

$$Response_{dB} = 20 \log (Response \text{ average}/40^\circ). \quad (4)$$

The corresponding difference response thresholds, as a measure of variability, were calculated similar to (3) but with the standard deviation of the individual subjects' responses as follows:

$$\Delta R_{dB} = 20 \log ((Response + \text{standard deviation})/Response) \quad (5)$$

Statistically significant differences of THR_{dB} , MAX_{dB} and DR_{dB} measured at the beginning and the end of the experimental session were calculated using the two tailed t -test for related samples with data from all subjects along with the Cohen's D effect sizes, where values of 0.2, 0.5 and 0.8+ are defined as small, moderate and large, respectively (Gravetter and Wallnau 2004).

To characterize the relation between stimulus and response within the subjects' DRs, we used the exponent of the Stevens' Power Law $\Psi = \beta \Phi^\alpha$, where Ψ represents the perception of the stimulus (subjects' responses), Φ represents the physical intensity of the stimulus (Voltage amplitude in our study), β is an arbitrary constant determining the scale unit and α is the power exponent that is used as a sensitivity index of the sensory system because it quantifies the relation between stimulus and perception (Gescheider 1985).

The Power Law exponent α can be estimated from the log-log function,

$$\log (\Psi) = \alpha \log (\Phi) + \log (\beta) \quad (6)$$

either directly for the CMM data or indirectly from the JND data (Gescheider 1985). For CMM we used the regression model

$$\Psi_{CMM \text{ dB}} = \alpha_{CMM} (SL_{dB}) + 20 \log (\beta_{CMM}) \quad (7)$$

where $\Psi_{CMM \text{ dB}}$ is the CMM response in dB (R_{dB}) and $SL_{dB} = 20 \log (Voltage \text{ selected}/THR)$ was the sensation level derived as the intensity of the reference voltage with respect to THR in dB. Note that we used SL_{dB} to minimize the deviation from the power law at lower stimuli

and the variability in THR values among subjects (Gescheider 1985). This approach resulted in more homogeneous regression coefficients (see Results). The same regression model was used for JND but $\Psi_{\text{JND dB}}$ was indirectly obtained by applying Fechner's Law (Coren et al. 2003) and transforming the data to dB as follows:

$$\Psi_{\text{JND dB}} = 20 \log \left[\frac{V}{\Delta V_{\text{mn}}} \ln(V/\text{THR}) \right] \quad (8)$$

This conversion of JND data to the Stevens' law equation follows the basis of Ekman's Law and provides a limited but useful way to compare sensitivity to differentiate (JND) and identify intensity levels (CMM)² (Gescheider 1985). Additionally, to prevent floor and ceiling effects, we discarded THR and MAX values, respectively, when calculating the regression coefficients for both CMM and JND.

In addition to characterizing the relation between perception and stimulation, we were also interested in estimating the amount of intensity coding information that may be transmitted using electrotactile stimulation on the tongue. This estimation consisted of calculating the number of JNDs (or discriminable intensity steps) that would fit in the span of each subject's DR. For the JND data, the number of steps was obtained by dividing the DR_{dB} by the mean of the ΔV_{dB} s above THR and below MAX:

$$\text{STEPS}_{\text{JND}} = \text{DR}_{\text{dB}} / \Delta V_{\text{mn dB}} \quad (9)$$

For the CMM data, the estimated number of steps that the perceptual range can be subdivided into was calculated by dividing the response range ($(\text{Response Range})_{\text{dB}} = 20 \log (\text{Response}_{\text{MAX}} / \text{Response}_{\text{V12.5\% of DR}})$) by the average of difference response thresholds from above THR and below MAX:

$$\text{STEPS}_{\text{CMM}} = (\text{Response Range})_{\text{dB}} / \Delta R_{\text{mn dB}} \quad (10)$$

The method we used for estimating the number of discriminable steps was preferred over cumulative difference thresholds because it is more conservative. Furthermore, the latter procedure has shown to be strongly weighted by large ΔV_{dB} s near THR and small ΔV_{dB} s near MAX levels (Nelson et al. 1996). We also used a one-way ANOVA with post-hoc Tukey test for multiple comparisons at $\alpha = 0.05$ to assess possible differences in ΔV_{dB} and ΔR_{dB} at different DR levels.

A significance level of $P < 0.05$ was used for all comparisons. Results are reported as averages $\pm$ standard deviations of across subjects' data.

²A more direct comparison of psychophysical sensitivity to intensity discrimination and identification can be obtained by using a methodology introduced by (Durlach and Braida 1969). However, this methodology limits responses to be ordinal and verbal, which would have restricted the objectives of our study.

Results

Dynamic ranges

The subjects' average magnitude of DR_{dB} at the beginning and end of the experiment were not significantly different from each other (overall 17.39 ± 2.30 dB; $P > 0.05$ with small effect, Cohen's $D = -0.08$) regardless of the method used to compute DR (staircase method or method of adjustment) (Figure 3A). However, even if the two average DR_{dB} s were similar, across-subject variability in their average responses appeared larger at the beginning than at the end of the experiments. This difference was statistically significant only for the method of adjustment (Levene's test for variances homogeneity, $P < 0.01$). Examination of the DR_{dB} points obtained through the staircase method (Figure 3A) suggests that subjects 1 and 6 may have had trouble defining their true DRs at the beginning of the experiment since their DR_{dB} s are far from the average at the beginning of the experiment and drastically drifted towards the average DR_{dB} at the end of the experiment. We found an overall increase in both THR_{dB} and MAX_{dB} after long exposure to electrotactile stimulation (see Figure 3B) resulting in an upward shift of DR_{dB} (shift of DR_{dB} not shown in Figure 3A). These increases were significant in the paired t -test ($P < 0.001$; large differences' effect sizes, Cohen's $D > 1$; overall average increment of 12.60 ± 11.40 % for THR and 5.93 ± 6.21 % for MAX levels including both methods).

To assess biases introduced by our psychophysical methods, we compared the perceptual measures obtained with the staircase vs. adjustment method. As expected, THR_{dB} s obtained with the staircase method were slightly lower than for the method of adjustment (t -test $p < 0.01$; Figure 3B). Conversely, MAX_{dB} did not significantly differ between methods, so the calculated DR_{dB} was found to be larger for the staircase method than for the method of adjustment (t -test $p < 0.01$; see Figure 3A).

Intensity discrimination (JND)

When subjects were asked to discriminate intensity stimulation levels within their DR_{dB} , the magnitude of the intensity increment/decrement in dB needed for the stimulus to feel different, ΔV_{dB} , decreased as the sensation level approached their MAX_{dB} (Figure 4A). These ΔV_{dB} magnitudes and the negative trend were very similar for all subjects. Note that the negative trend was non-linear as the largest significant drop in ΔV_{dB} (average 56.8%) occurred from THR_{dB} to 12.5% of DR, followed by lower but significant decrements of ΔV_{dB} at different points beyond this level (drops averaging 16.9%; Tukey post-hoc for multiple comparisons at $\alpha = 0.05$; Figure 4A). We calculated that the DR_{dB} could, on average, be subdivided into 10 ± 3 discriminable steps or JNDs (right of Figure 4A).

From the pattern of ΔV_{dB} s we calculated perception of the stimulation, $\Psi_{JND\ dB}$ (see Methods). This variable was closely related to sensation level, SL_{dB} , of the stimulation intensity, being similar for all subjects (Figure 5A) as revealed by α_{JND} values slightly above 1 and intercepts close to zero. Mean α_{JND} and intercepts were 1.51 ± 0.3 and -1.51 ± 3.88 , respectively. The intercepts were more negative and were less consistent across subjects when using V_{dB} in the regression model (-31.75 ± 14.30) than SL_{dB} , whereas mean α_{JND} was unaffected by this change.

Intensity matching (CMM)

When subjects were asked to match the stimulation levels within their DR with the angles from the protractor's range corresponding to stimulation levels, the amount of intensity underestimation increased with increasing intensity (Figure 6). In other words, subjects tended to guess smaller angular excursions than those actually associated with the intensity levels. This trend was especially clear in subject 6, but much less in the rest of the subjects, with

subjects 1 and 5 being characterized by the most accurate intensity estimation. Despite these underestimation trends, the majority of the relations (6 out of 8) between intensity and estimation had slopes larger than 0.8, indicating that subjects were generally accurate in matching ETS levels with protractor angles.

Response variability (ΔR_{dB}), unlike accuracy trends and ΔV_{dB} s from the JND protocol (Figure 4A), did not follow a similar trend among subjects. Additionally, variability was generally larger with respect to the response range than for JND, which in turn gave lower estimations of the number of levels subjects were able to differentiate in the perceptual range (8 ± 1).

Similar to the performance underestimation, perceptual increments were smaller than constant increments in stimulus intensities ($\alpha_{CMM} < 1$). In fact, the slopes or α_{CMM} of the regression line of $\Psi_{JND\ dB}$ vs. SL_{dB} averaged 0.60 ± 0.07 (Figure 5B), this being equivalent to a shrinkage of the perceptual DR. As in JND, the slopes were also associated with relatively low intercepts (-1.89 ± 1.77). It is important to point out that all α_{CMM} values were below the slopes representing their performance (average 0.60 ± 0.07 from Figure 5B vs. 0.87 ± 0.12 from Figure 6). This discrepancy comes from the fact that the range of responses in dB was small compared with subjects DR_{dB} . Note also that only subjects 1 and 6 have regression lines that considerably differ from the rest (Figure 5B). These two subjects also had extreme α_{JND} and β_{JND} values (Figure 5A) and were characterized by DR_{dB} s with large differences between the beginning and end of the experiment (see above).

Discussion

Our study revealed that subjects can effectively identify and discriminate electrical stimuli on the tongue, partly due to a high and relatively constant magnitude in the dynamic range despite a slight drift after prolonged exposure. Unlike discrimination of electrical stimulus intensity on other skin areas of the body, we found that discrimination of ETS on the tongue improved with increasing stimulus intensity. Overall, subjects in general accurately estimated and matched stimulus intensity by changing protractor angles, even though a slight increase of underestimation as intensity increased was found. Below we discuss the potential neural mechanisms underlying the above results and their relevance for sensory substitution/augmentation applications.

Dynamic ranges

On average our electrotactile DR_{dB} is higher than most DRs reported for other tactile loci (range: 6 dB to 20dB; see review by Kaczmarek and Bach-y-Rita 1995), which correlates with a better sensitivity index (see below). There are three conditions where THR and MAX levels would produce larger DR_{dB} s on the tongue: 1) lower THR and higher MAX, 2) lower THR with similar MAX, or 3) similar THR with larger MAX. We believe the first is most likely to be the case due to the tongue's high conductivity, uniform stimulation dispersion, short distance the afferents and the source of electrical stimulation and a large amount and type of afferents (Kaczmarek et al. 1991; Marlow et al. 1965). These factors are likely to facilitate recruitment of afferents at low intensity levels (low THR levels, hence tongue's high sensitivity to ETS). Similarly, as electrical stimulation is likely to more uniformly spread through the tissue due to the presence of saliva, more mechanoreceptor afferents will be activated without producing pain caused by high density spots (higher MAX levels; Mueller et al. 1953). Only the lips have shown similar THR levels, but these are inconveniently accompanied by lower DR_{dB} s (Liu and Tang 2005).

The above factors might have contributed to the relative stability of DR_{dB} magnitudes, this being particularly clear at the end of the experiment (Figure 3A). The small upward DR_{dB} drift derived from the THR_{dB} and MAX_{dB} levels' elevation may result from peripheral adaptation

and/or central habituation (Kandel et al. 2000; Von Békésy 1960; Figure 3B). THR drift in tactile loci with mechanoreceptors sharing similar response characteristics as the tongue (Marlow et al. 1965; Trulsson and Essick 1997) appears to be affected by duration and strength of ETS. Specifically, large percentages of THR drifts have been reported for strong stimulation levels and long duration ETS on the abdomen (Kaczmarek et al. 1990, 2000).

Intensity discrimination

We found that subjects' ability to discriminate the tongue's ETS intensities requires large intensity increments/decrements in dB close to THR and smaller changes as intensity increases above 12.5% of the DR (Figure 4A). Low sensitivity to changes around THR is a well-known psychophysical phenomenon (Baird 1997; Woodworth and Schlosberg 1954) and is interpreted as due to the difficulty in overcoming the spontaneous neural activity at low levels of stimulation (Gescheider 1985). In contrast, subjects' ability to discriminate the tongue's ETS intensities improved at higher stimulus intensities. Surprisingly, this result is not consistent with reports of flat, decreasing or variable discriminating ability from other sensory modalities and tactile sites (Aiello and Valenza 1984; Coren et al. 2003; Saunders and Collins 1971). We find two conditions that could explain this discrepancy as stimulation on the tongue may produce: (1) excitation of an increased number of sensory afferents with similar response characteristics as intensity increases and (2) excitation of sensory afferents responsible for coding intensity changes.

Increased recruitment (1) is facilitated by a highly conductive interface that assists an even dispersion of current and proximity to the nerves transmitting the sensory information present in the tongue. This also explains previous work where the amount of transmitted information for intensity modulation was greater for electrical nerve stimulation (Anani et al. 1977) than for electrocutaneous stimulation on the hand (Kato et al. 1970). Furthermore, our results are comparable to those from studies of cochlear implants (Kreft et al. 2004; Nelson et al. 1996; Pfingst et al. 1983). In these studies a major difference was the use of biphasic pulses, which should not affect the advantage of current dispersion.

An increase recruitment has a great impact on the transmission of intensity information in this context, due to the fact that each touch afferent can only encode a small range of stimulus intensities (Kaczmarek et al. 2000). However, activating an increased number of rapidly adapting afferents (2) would convey information about stimulus intensity changes (Trulsson and Essick 1997) more efficiently. It is likely that stimulation mostly excited these type of afferents, as these constitute the majority (2/3) of mechanoreceptors of the tongue's superficial layer (the remaining 1/3 being slowly adapting afferents) (Trulsson and Essick 1997). Interestingly, surface rapidly adapting afferents also outnumber slowly adapting mechanoreceptors in the glabrous skin of the fingertip (Johansson and Vallbo 1979). As rapidly adapting receptors are responsible for encoding intensity changes (Johnson et al. 2000), this anatomical organization would support explorative and manipulative behaviors commonly performed by the hand and tongue.

Intensity estimation

We found that even though, on average, subjects are able to estimate stimulus intensities when representing them using protractor angles (Figure 1A), there was a slight trend among subjects to increasingly underestimate intensity as it increased (Figure 6). We attribute a resultant narrowing of the response range as a progressive propensity to estimate values towards a value (mean, median or preferred), quantified as the level of minimum estimation error bias, due to the necessity of using memory to recall DR and allocating a given stimulus intensity within it. This phenomenon has been described previously as contraction bias (Jou et al. 2004) and

underlines the difficulty of recalling DR as well as relating present stimulus intensity with an accurately recalled DR (Baird 1997).

Sensitivity index

Sensitivity indices of ETS were used to quantify subjects' ability to perceive constant changes in stimulus intensity. These indices indicate that stimulus intensity perception does not exactly mirror actual stimulus intensity, rate of perceptual changes being larger for JND or smaller for CMM than constant increases in stimulus intensity (Stevens' exponents averaged across all subjects: 1.5 and 0.6, respectively; Figure 5).

Discrepancy between JND and CMM indices may be due in part to methodological differences as described in the psychophysical literature (Stevens 1975). Specifically, the boundaries and discontinuity of responses imposed by the CMM protocol might have biased subjects' performance. Additionally, having to rely on memory (as subjects did in CMM) to judge magnitudes has been shown to elicit smaller indices than when magnitudes are perceived (Moyer et al. 1978). Therefore, as JND does not have these and sensory translation limitations, it may be a more reliable indicator of the tongue's ETS sensitivity.

Our JND indices are similar to those found by an electrogustometry study (1.2 in Salata et al. 1991) and closer to one than most other tactile loci (as high as 3.5 for human skin; Kaczmarek and Bach-y-Rita 1995), both assessed through ETS. The large difference between the tongue and other ETS sites is likely due to the latter's larger DR_{dB} s, since the magnitude of Stevens' exponent and DR_{dB} s being shown to be inversely proportional (Baird 1997).

Differentiable intensity steps

Our calculations of the DR_{dB} subdivisions indicate that naïve subjects are slightly better at differentiating when they had to compare ETS stimuli of different intensities (JND protocol; Figure 4A) than when they had to estimate the stimulation with another modality (CMM protocol) intensity levels. This is expected since it has been shown that giving responses using the same sensory modality (intra-modal estimation) produce smaller errors than when another modality is used (cross-modal estimation) (Appelle 1971; Bjorkman 1967). It has also been suggested that this is due to the fact that cross-modal estimation uses only common - and not specific - aspects of the stimulus to make judgments (Bjorkman 1967), thus causing a loss of information.

Aside from methodology restrictions, the number of discernable steps is also limited by the channel capacity of humans to transmit received information, which has been suggested and shown to include 7 ± 2 pieces of information (Miller 1956). Our average number of CMM identifiable steps (8 ± 1) closely relates to this number, which indicates that the $STEPS_{CMM}$ might be a more realistic and practical estimate.

Notes on Applicability

Our results suggest that sensory substitution/augmentation applications using ETS on the tongue would be superior to other tactile loci. This assertion is supported by a generally better fit to the recommended performance criteria for ETS (see above). These criteria include (but are not limited to): 1) maximal DR; 2) minimal variation of THR and MAX levels; 3) maximal information transfer measured by small difference thresholds and minimal error in estimating absolute stimulation levels; 4) maximal number of steps into which DR can be subdivided; and 5) minimal power consumption (low THR levels) (Kaczmarek and Bach-y-Rita 1995; Szeto and Riso 1990).

In addition to having large DR_{dBs} on the tongue, their general consistency suggests that subjects familiarize fairly rapidly to ETS. This phenomenon may significantly reduce training time to obtain plateau measures (originally 14 days proposed by Szeto and Riso 1990), which may in turn contribute to a common, thus predictable, performance.

According to our results, it is expected that a stimulus level slightly higher than THR (e.g., 12.5%) is expected to be less biased to subjects' temporary judgment (discrimination and estimation) of perceived intensity yet large enough to overcome neural noise and drift. Notice that the ability to recognize, interpret, classify and utilize electrotactile information may improve with training (Szeto and Chung 1986; Szeto and Chung 1985). Also, our estimations apply only under the conditions reported in this study and in applications that would involve similar tasks. Lastly, inferences about applicability and comparisons with other body parts need to be experimentally assessed to further characterize differences in peripheral and central factors responsible for sensory processing. Furthermore, preference on the stimulation location (tongue versus other tactile areas) would depend on practical and personal factors. For example, subjects may not desire to use an intraoral tongue stimulator either because they may feel uncomfortable and/or because it would interfere with the use of the tongue for speech. To overcome some of these limitations, a wireless retainer for tongue electrotactile stimulation is being developed (Dr. Yuri Danilov, personal communication). Additionally, we believe that our findings may help optimize sensory substitution/augmentation systems including those already used for clinical applications (e.g., Danilov et al. 2007).

Conclusions

Our results show that the sensory system and bioelectrical properties of the tongue allow reliable and stable transmission of ETS intensity information. This was found despite minimal practice with the ETS protocol as well as a slight drift in sensation occurring after strong and prolonged exposure to ETS. The pattern of differentiation and estimation of ETS intensity suggests a significant involvement of rapidly adapting mechanoreceptor afferents. These results may aid the design of optimal codes for sensory substitution/augmentation applications.

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Appendix

Appendix A. Method of adjustment and parameter value selection for DR and JND protocol

Based on suggestions by Garcia-Perez (2000, 2001), we opted to use the method of adjustment to quickly find the target levels of interest (THR, MAX and ΔV s of reference voltages within the span of DR). This provided subjects with experience of the percepts and the experiments and also a basis for the initial voltages and step sizes to minimize the number of trials.

For the DR protocol, each of the 5 THR and MAX voltage measures was recorded in a trial in which subjects adjusted the amplitude of the stimulation until they felt the most precise THR or MAX levels by turning the knob (Figure 1) up and down, starting from zero. The voltage

delivered to the tongue started to increase from zero when it reached a point (0-30 %) of the knob's range of rotation that randomly changed from trial-to-trial. This was done to prevent biasing subject's estimation based on kinesthetic cues and was also used in the JND protocol (see below). Trials that lasted longer than 20 s were discarded and repeated to minimize the adaptation effect after long exposure to ETS (Kaczmarek 2000). Once the voltage level was selected, subjects released the knob and pressed ENTER to input the value. Subjects then had a 10 s inter-trial delay and were asked to turn the knob back to the start position and prepare for the next trial.

For the JND 2-AC method ΔV s for each reference voltage were obtained by running one ascending and one descending sets (counterbalanced) of reference voltage trials. For the initial adjustable voltage for the $\Delta V_l/\Delta V_u$ search of each reference voltage, we decreased/increased the reference voltage 0.5 times the average ΔV (including the two measures of the each ΔV).

In the ascending method of adjustment the set of trials containing each of the 9 reference voltages had two sub-trials, one for ΔV_l and one for ΔV_u . In each of the ΔV_l sub-trials, subjects modulated the amplitude of the adjustable voltage by turning the knob (Figure 1) until it matched the perceived intensity of the reference voltage. Both stimuli were presented for 0.3 s sequentially and continuously with a delay of 0.2 s in between with an auditory cue identifying the reference voltage. Once subjects entered the adjustable voltage level, they turned the knob down, waited 1 s and continued to find ΔV_u . For ΔV_u , the adjusted voltage started at the reference voltage level and subjects were instructed to find the voltage level that made both stimuli feel different. Once this response was entered, subjects turned the knob down and waited 10 s for the next trial. The descending method of adjustment followed a similar protocol starting at MAX and finding ΔV_u followed by ΔV_l . At least 2 minutes of rest were given between the ascending and descending set of trials.

These voltages obtained with these protocols were used to calculate the voltage at the first trial, selected at a mid point (50%) between the initial voltage (zero for THR and MAX measures or the reference voltage for ΔV_u and ΔV_l measures) and a mean estimate obtained with the method of adjustment. The step-up size was calculated as 0.7 times the standard deviation (SD) of these estimates. This step-up/SD ratio chosen was greater than that originally suggested in (1/3; Garcia-Perez 2001), as it was expected to considerably decrease the amount of trials given the results of a similar ratio used in the force-choice staircase method in Garcia-Perez (2000). Asymptotic convergence was found stable with step-down size of 0.871 and 0.5488 times the step-up size for the staircase and 2-AC method, respectively. To prevent too large or small step-up sizes, their sizes were arbitrarily restricted to be between 0.1 V and 1.2 V.

Appendix B. Stimulation device

The TDU (Figure 1B) is a programmable, positive mono-phasic pulse, voltage-controlled generator with a capacitively-coupled output for zero net direct current to minimize irritation. The device delivers patterned voltage pulses (maximum output: ~24.2V) to a flexible electrode array (Figure 1B and C). Digital conversion limited voltage step changes to ~100 mV, thus allowing for 255 equally spaced steps. The TDU output resistance and the tongue electrode resistance were ~1.1 k Ω and ~2 k Ω , respectively. Each active electrode in the block received the same waveform parameters and its activation was staggered so that adjacent electrodes were never simultaneously pulsed and would function as a return ground pathway. The delay of this activation (469.4 μ s) was calculated by dividing the inner burst period (16.9 ms) by 36 electrodes (right or left half of the total array) so that all the electrodes of the sub-block would be activated within an the inner burst period. Stimulation was delivered through a mono-phasic pulse, voltage-controlled waveform with a pattern of 3 individual 40 μ s pulses within the 16.9 ms period grouped into bursts with a 70 ms period (based on C Lozano and KA Kaczmarek's

unpublished observations of the greatest magnitude-estimation-based dynamic ranges for tongue ETS).

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Figure 1. Experimental setup and electrotactile display

(A) The setup consisted of a computer, tongue stimulator, Tongue Display Unit (TDU) (B), and a protractor (radius = 12.5 cm; shaded arch from 40° to 140°). The handle of the protractor was attached to a potentiometer connected to one analog input of the TDU. The computer was used to send and receive information to and from the TDU. Subjects used the keyboard to enter their responses and the computer monitor to receive task instructions. (B) The TDU delivered the stimulation to the flexible electrode array placed on the tongue. The output voltage of the stimulation was modulated through the knob operated by the subject. (C) Illustration of the electrode array placement on the tongue, for which consistency was achieved by touching the plastic landmark with the tip of the tongue. (D) Electrode dimensions and center-to-center inter-electrode spacing.

Figure 2. JND Protocol: forced-choice method to obtain upper and lower difference thresholds (ΔV s) for each reference intensity level

The ordinate shows the intensity levels (voltages) of the electrical stimulation on the tongue. The abscissa illustrates the order of events for a set of trials. **(A)** Representation of events and subject tasks (see text). Filled and open triangles indicate the actions required from the subject. Dashed line indicates the initial stimulus voltage. **(B)** Illustration of voltage changes in a complete set of trials. Circles indicate the level of stimulation used to obtain the stimulus intensity average. Figure not to scale.

Figure 3. Dynamic ranges and stimulation levels for all subjects

Values were obtained with staircase method and method of adjustment. Graphs show subjects' average responses of DR_{dB} (**A**; equation (2)) and stimulation levels (THR_{dB} in white and MAX_{dB} in gray; **B**; equation (1)) obtained at beginning and end of the experiment. The lines connecting the points illustrate changes of individual subjects' average responses after long exposure. Horizontal line-bars on top with asterisks show values that are significantly different from each other (*t*-test at $\alpha = 0.05$). Brackets on the horizontal line-bars indicate the method comparisons.

Figure 4. Difference thresholds for JND and CMM measures

Graph shows each subject's average of the upper and lower ΔV_{dB} s (A; equation (3)) for each reference voltage (represented as a percent of the DR). Dotted line shows the overall average. Horizontal bars (without asterisks) indicate no significant differences; the rest of pairwise differences are significant (Tukey post-hoc for multiple comparisons at $\alpha = 0.05$). Calculated number of steps indicated in table (equation (9) for A and (10) for B).

Figure 5. Sensation curves for JND and CMM
Graphs show the sensations elicited by the stimulation intensities V_{dB} within subjects' DRs for each of the two protocols. (A) Sensation regression curves indirectly obtained from the JND data (equation (8)). (B) Sensation regression curves obtained from the CMM data (equation (7)). The average scale unit values of Stevens' Law ($\beta = 10^{(\text{intercept}/20)}$) were: $\beta_{\text{JND}} = 0.92 \pm 0.05$ and $\beta_{\text{CMM}} = 0.82 \pm 0.17$, respectively.

Figure 6. CMM responses

Graph shows the responses expressed as percentages of the protractor's range representing the percentage of subjects' DR. Gray line shows the identity regression or perfect match (i.e., slope = 1, $R^2 = 1$). Dotted lines represent trends observed in subjects' responses. The slope of the regression where the intercept crosses at the origin (% protractor's range = slope (% DR)) and level of fit (R^2) for each subject is indicated on the label.