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Spatial Mapping of Electrotactile Sensation Threshold and Intensity Range on the Human Tongue: Initial Results

Mitchell E. Tyler, *Member IEEE,* Jacquelin G. Braun, and Yuri P. Danilov

Abstract

We have developed a novel, tongue-based electrotactile brain-machine interface. Variability of the tactile sensation intensity across the stimulated area, however, limits the amount of reliable information transmission. We have conducted an experiment to characterize local sensitivity across the region stimulated by the array. From this data we have constructed an iso-intensity algorithm to compensate for the variability in electrotactile sensation levels across the stimulated area of the tongue.

INTRODUCTION

We have developed an electrotactile stimulation (ETS) system for the human tongue that can be used to present either information for a variety of sensory substitution applications, e.g. vision, or head orientation in balance control [1-5], or for neuromodulation and rehabilitation after neural injury [6-8].

In preliminary tests during the development of this interface, however, we found that perception of sensation intensity and dynamic range of ETS on the tongue is not uniform, varying as a function of location, both in the medial-lateral and anterior-posterior directions. This variability is likely due to three factors: the differential innervations of the tongue, and to both the type and density of tactile the receptors stimulated. The various tactile sensors in the anterior aspect of the tongue are innervated by 2 cranial nerves (CN): the lingual branch of the trigeminal nerve (CN-V), and the chorda tympani branch of the facial nerve (CN-VII). Additionally, receptor densities are highest at the tip of the tongue, slightly lower at the lateral perimeter, and progressively decline toward the posterior and midline [9-11]. The electrode array we have developed spans all these regions, leading to substantial differences in the perceived intensity of the tactile sensation as a function of the stimulus location.

Given the evidence from the literature, as well as our preliminary observations, it was resolved that psychophysical experiments were necessary to develop a spatial map of the electrotactile percept intensity across the stimulated area. Having this knowledge, we can then ensure that any ETS pattern presented across the tongue display may be adequately and uniformly perceived by using an algorithm designed to specifically compensate for the differences in local tactile sensitivity by adjusting the relative stimulation amplitude.

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M. E. Tyler is with the Dept. of Biomedical Engineering, and Dept. of Rehabilitation Medicine, University of Wisconsin-Madison, Madison, WI 53706. e-mail: metyler1@wisc.edu, 608.265.3756

J. G. Braun was with the Dept. of Psychology, University of Wisconsin-Madison, and is now in private clinical practice in Columbia, N.Y.

Yuri P. Danilov is with the Dept. of Rehabilitation Medicine, University of Wisconsin-Madison, Madison, WI 53706.

BACKGROUND

The tongue, along with the lip and fingertip, differ from other body sites in their specialization for spatial perception acuity. Previous studies have demonstrated that the tongue is even more sensitive than the fingertip on the basis of mechanical two-point discrimination thresholds [6]. These investigations of tongue tactile sensitivity were, however, limited measurements to the tip of the tongue, and none address ETS. To address this gap in knowledge, we have demonstrated that geometric pattern perception by electrotactile stimulation on the tongue is as accurate as that for the fingertip [12-14].

The tongue is uniquely suited for electrotactile stimulation because in the protected environment of the mouth there is no corneal or protective layer of skin typically found on external body surfaces (particularly the hands and feet). Additionally, the cutaneo-sensory receptors are close to the surface of the tongue, and it is continuously bathed with saliva, an effective electrolyte. Consequently, the tongue is an attractive candidate for a non-invasive electrotactile brain-machine interface. We have found that the tongue requires only about 3% of the voltage (10-20 V), and far less current (1-4 mA), than the fingertip to achieve equivalent sensation levels [15,16].

METHODS

In order to create an initial electrotactile sensitivity map of the tongue, three ETS intensity levels were selected: “Aware" (just supra-threshold), “Comfortable" (moderate intensity), and “High Tolerable" (high intensity without discomfort). These were chosen because we were particularly interested in determining not only sensation thresholds as a function of stimulus location, but also in establishing the range of useful sensation available across the entire array area.

Design. Sixteen discrete, non-overlapping ‘blocks’ of 9 electrodes (in a 3x3 square pattern) were defined for the purpose of characterizing both the local sensation threshold and useful range of sensitivity of the tongue during ETS on the array. The 16 test blocks correspond to the regions defined by intersection of 4 anterior-posterior oriented Columns (two medial and two lateral, symmetric about the midline), and by 4 Rows (front, mid-front, mid-back, and back). Using repeated a measures method, randomly ordered data samples for each the sixteen sensation regions at the 3 suprathreshold sensation intensity levels on the tongue were collected from each subject.

Procedure. Six adults (3 M, 3 F, mean age 23.1 yrs, SD=3.6 yrs) participated. All subjects were familiar with tactile psychophysical experiments and with electrotactile stimulation on the tongue. For each trial, the subject was instructed to adjust a general intensity control knob on the waveform generator from zero to reach one of the 3 specified intensity levels. Each subject completed 80 trials (5 random reps at each of 16 blocks of electrodes) at each of the three intensity conditions. Under the Aware or sensation threshold condition, participants were instructed to adjust the intensity to the lowest setting at which they were just able to clearly sense the pattern presented on the array. Under the Comfortable condition, participants were instructed to set the intensity of the test block at a level they felt they could use for chronic stimulation (e.g. several minutes). Under the High Tolerable condition, participants were instructed to adjust the intensity to a level that was intense but not painful, i.e. could be tolerated for a relatively short period of time (10 seconds).

Electrodes: Electrotactile stimuli were delivered to the dorsum of the tongue via a flexible electrode array (Fig. 1) placed in the mouth (Fig. 2), and held lightly between the lips. The 12 x 12 tongue electrode array measures 30 mm square, and is created with the same photolithographic techniques used for flex circuits. The 1.5 mm diameter electrodes are spaced on 2.34 mm centers on the 100 µm thick polyester laminate material and are gold plated for biocompatibility. The cable is connected to a custom electrotactile pattern generator.

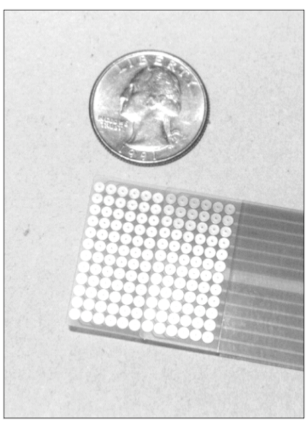

Fig 1. A 12x12 electrode array.

Fig 2. Array placed on tongue.

Waveforms: The electrotactile stimulus, produced by a custom 144-channel waveform generator, is a burst of three 40-µs pulses delivered at a rate of 50 Hz with a 200 Hz pulse rate within a burst. The stimulation was delivered simultaneously to all 9 electrodes in the 3x3 pattern. This waveform structure was shown previously to yield strong, comfortable electrotactile percepts [7]. Positive pulses under voltage control (nominal impedance $Z_{out} = 1.13$ kΩ), were used because they have previously been demonstrated to yield both lower sensation thresholds and superior stimulus quality on the fingertips [13]. The load impedance is nominally 1.5-2 kΩ at suprathreshold stimulation levels on the tongue, and the stimulation electronics were controlled by a PC running custom software operating.

RESULTS

A repeated-measures analysis of variance was conducted on the collected data. The effects of stimulation condition (i.e., Aware, Comfortable, and High Tolerable) by block location on the array was analyzed. The results, averaged across the six subjects, and collapsed across [left / right], are presented in Figure 3 as a percentage of maximum stimulation intensity (25.4 volts) required to achieve the particular sensation condition. The average relative thresholds values for the Aware, Comfortable, and High Tolerable conditions were 20.6% (5.23 V), 43.8% (11.13 V), and 66.7% (16.9 V), respectively [$F(2,10) = 60.50$, $p < .001$]. As expected, the obtained values were also found to increase by Row as the test stimulus was presented farther back on the tongue [$F(3,15) = 85.45$, $p < .001$]. The effects of position (Row x Column) on the tongue, interacted [$F(6,30) = 3.47$, $p = .01$], although effects of [left / right] were not significant, signifying that the responses were symmetric about the midline. Looking at the results by Row, the Comfortable and High Tolerable conditions produce a greater relative increase in voltage (moving from front to back of the tongue) than did the Aware threshold condition. Additionally, the measured sensation values for all 3 intensity levels were also higher for the lateral Columns on the tongue than for the medial ones [$F(1, 5) = 7.79$, $p = .04$]. There was also an interaction with Rows [$F(3,15) = 5.72$, $p < .01$], such that the increase in threshold from front to back on the tongue was greater for the lateral regions relative to the medial ones. There were no other significant interactions, [all $p < .05$].

The analysis also revealed that the High Tolerable condition lead to significantly higher mean voltages than did Comfortable [$F(1,5) = 40.86$, $p < .01$]. The mean voltage increased from the front to back [$F(3,15) = 95.96$, $p < .001$], and the lateral columns had higher means than did the medial ones [$F(1,5) = 11.28$, $p < .05$]. Most importantly, however, is that there were no interactions between these two elevated intensity levels, (i.e. all $F < 1.15$, all $p > 0.35$). This means that the Comfortable and High Tolerable conditions differed from Aware only by a single proportionality constant. That is, they have the same relative sensation intensity pattern across the area of stimulation on the tongue.

We also found an interaction of Row x Column between front / back position and medial / lateral positions on the tongue when analyzing only the Comfortable and High Tolerable data [$F(3,15) = 6.39$, $p < .01$]. A trend analysis was conducted that showed this interaction was strictly due to a linear interaction between the two factors [$F(1,5) = 9.13$, $p < .05$]. That is to say, the mean percept levels increased linearly by Rows from front to back of the stimulation region for these two intensity level conditions, but differed in terms of the rate of change. We consequently fit the data from the lateral and medial portions of the tongue, collapsing the results across the Comfortable and High Tolerable conditions to a linear regression line. The results confirmed our earlier observations that the increase in voltage required to achieve the specified percept magnitude, moving from the front to the back of the tongue by Row, was more rapid for the lateral columns than for the medial ones. This is also observable in Figure 3.

It appears that the change in slope of the lateral and medial portions of the tongue is due to a difference in sensitivity across the front of the tongue. Post-hoc tests confirmed this observation. At the front, the lateral region was less sensitive than the medial region [$F(1,5) = 23.42$, $p = .005$], whereas there was no difference between the lateral and medial regions at the rear of the array on the tongue, [$F<1$] for this stimulation pattern.

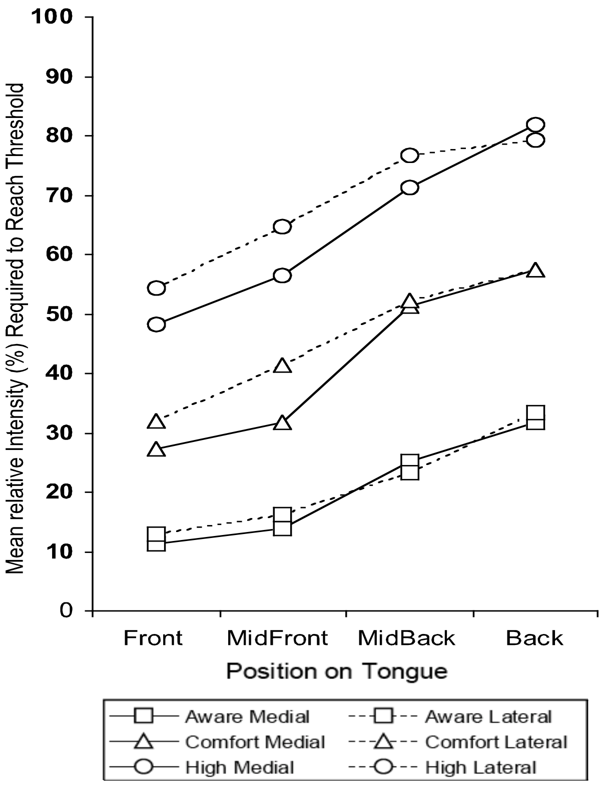

Figure 3. Mean Relative Sensation Intensities for each of 3 stimulation levels (Aware, Comfortable, and High-Tolerable) across 16 discrete 3x3 electrode regions or 'blocks' on the tongue. Differences between stimulation levels and between lateral vs. medial columns were significant. Differences in data from left and right sides of tongue were not significant. Relative percept magnitudes for each stimulus level are collapsed to a single line for the 2 medial and lateral columns.

DISCUSSION

The analysis of the data indicates that there is significant electrotactile percept inhomogeneity on the tongue, and offers indirect evidence of the effects of the type of innervations and wide differences in both densities and distributions of tactile fibers in the tongue. The results can be expressed as surface map of the differential intensity required, as shown in Figure 4. This can also be viewed as a measure of relative sensitivity to stimulation on the tongue, where the front-central regions of the tongue are the most sensitive to ETS, while the back of the array, still in the anterior half of the tongue, is approximately 30% less sensitive than the front. It is notable that there is a slight concavity in the anterior-medial region of the map, indicating that the sensitivity is relatively high and uniform in this area. The map also demonstrates that at the front the lateral columns are proportionally less sensitive than the medial regions, whereas the sensitivity is essentially uniform across the back of the array for this pattern. It is unclear whether these variations are due to the response characteristics of the tactile receptors themselves, excitation of the afferent fibers adjacent to the electrodes, or stimulation of free nerve endings and axons. Further research is required to discern the actors in the transduction of the physical stimulus to psychophysical response.

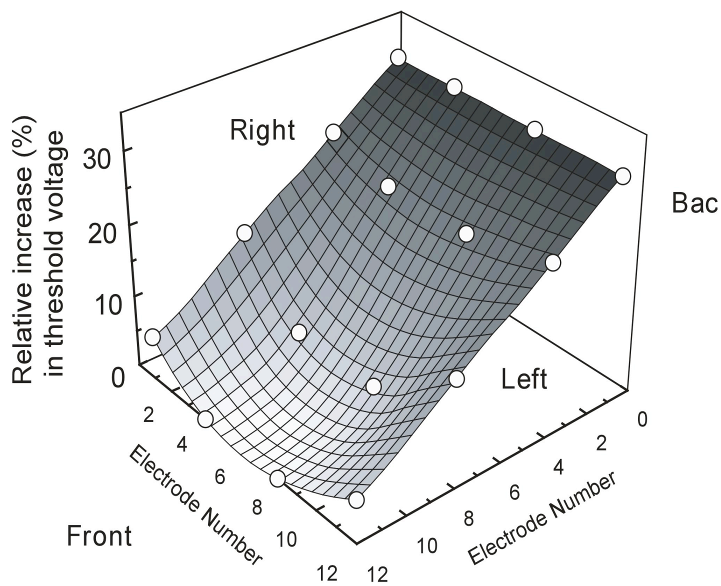

Figure 4. Sensation threshold intensity of electrotactile stimulation relative to the front-center region of the human tongue. Stimulus was 3x3 electrode contiguous pattern, yielding a 16-point data array. Note that relative threshold value is symmetric about the centerline, and increases progressively from front to rear of the stimulation area on the tongue. Overall stimulation area is a 30 mm x 30 mm region on the anterior portion (but not the tip) of the tongue.

Nonetheless, the results indicate that this sensitivity function is predictable, and is symmetric about the midline of the tongue. While the map shown in Figure 4 is for the

Awareness, the analysis reveals that same relationship holds true for both the Comfortable and High Tolerable conditions as well. These would appear as parallel conformal layers above the Aware condition surface map, with the amplitude of each being offset from the other by a simple constant.

The results demonstrate that while variable, the electrotactile sensitivity of the tongue can be quantified relatively easily, and by using analytic curve-fitting (polynomial), an iso-intensity amplitude algorithm can be created to specifically compensate for the variability of the electrotactile percept as a function of location on the array. After the compensated intensity value is calculated, the sensation in each tactile region can predictably altered so that the effective percept magnitude is constant across the entire stimulation area on the tongue. At this level of spatial granularity (3x3), adjustment of the mean overall intensity across the array is possible because of the statistically uniform dynamic range of stimulation across the area of the array, consequently making it possible to adjust the absolute intensity with a single scaling factor.

FUTURE WORK

At present, the experimental ETS system employs a simple scalar adjustment of the averaged intensity map shown in Figure 4 to provide a uniform and constant percept magnitude across the array for coarse patterns. Results from our more recent studies, however, indicate that this 'one-map-fits-all' approach is inadequate for displaying pictorial or graphic data, which require higher resolution for adequate content discrimination. In particular, we have observed that the shapes of the surface plots of threshold versus location for 2x2 and 1x1 stimulus patterns have more and greater amplitude undulations appearing as a saddle and trough. These observations point to the major influence of spatial summation has on the mean perceived intensity. Additionally, the present approach cannot accommodate individuals with other discrete anomalies in sensitivity. In the future we envision a mapping program interface will be easily customized so that an individual intensity profile can be generated for a specific user and circumstance. This would then be used to generate a personalized iso-intensity compensation map, assuring maximal sensation uniformity and therefore increasing the potential of the interface for useful information transmission through the tongue to the brain.

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