THESIS

EVALUATION OF ELECTRICAL TONGUE STIMULATION FOR COMMUNICATION OF AUDIO INFORMATION TO THE BRAIN

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2016

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ABSTRACT

EVALUATION OF ELECTRICAL TONGUE STIMULATION FOR COMMUNICATION OF AUDIO INFORMATION TO THE BRAIN

Non reparative solutions to damaged or impaired sensory systems have proven highly effective in many applications but are generally underutilized. For auditory disorders, traditional reparative solutions such as hearing aids and implant technology are limited in their ability to treat neurological causes of hearing loss. A method to provide auditory information to a user via the lingual nerve is proposed. The number of mechanoreceptors in the tongue exceeds the number of inner hair cells in the cochlea and the dynamic range of neurons in both systems is comparable suggesting that the achievable throughput of information in the lingual nerve is comparable to that of the auditory nerve. This supports the feasibility of transmitting audio information to the brain via the lingual nerve. Using techniques implemented in similar successful technology, the achievable throughput of the dorsal surface of the tongue using existing stimulation methods without additional innovation was estimated to be as high as 1,800 bits per second for an experienced user, in the same range required by many audio codecs used for spoken language. To make a more accurate estimation of achievable throughput, devices were developed to stimulate the tongue electrically, and an experiment to map the sensitivity of the tongue to a form of electrotactile stimulus was performed. For the population tested, discrimination ability of the tongue varied greatly. For all participants estimates for the immediately achievable throughput for the surface of the tongue was sufficient to communicate basic phonetic information to the participant. The estimated throughput for an experienced user was estimated to be as high as 1,400 bits per second. Lingual sensitivity maps were generated

that will allow researchers and developers to manufacture electrode arrays that can reliably stimulate lingual nerve endings in a discriminatory manner. In another study we tested the feasibility of sending audio information to a person via the tongue. Preliminary data are presented on participants in a learning study that were able to discern stimuli generated from recorded voices, supporting our hypothesis on immediately achievable throughputs.

ACKNOWLEDGEMENTS

I would like to thank all who have contributed to this work and supported me along the way. At the risk of leaving anyone out, I would like to specifically thank my parents, stepfather, brother, sister, and aunt for encouraging my interests in science and engineering, and in general helping me in any way they can. I would like to thank my beautiful girlfriend for believing in me always. I would like to thank my advisors and committee members, and specifically Dr. John Williams for giving me an opportunity that has become larger than I ever imagined, Dr. Leslie Stone-Roy, who, with Dr. Williams, has made this project flourish, Dr. Alicatore for introducing me to the world of mechatronics, and Dr. Malcom, for his interest, time, and consideration.

I would like to thank Dr. Stone-Roy's 2015 BMS 480 class for their hard work and analysis, without which, this thesis would not exist in its present form. I would like to express gratitude for the efforts of Dr. Phil Turk, Veronica Burt, Scott Abohn, Luke Chen, Pierce Vilkus, and Marina Rodrigues for their statistical analysis. I would like to thank the members of the CEPPE Lab and Plasma Controls who have supported this work in innumerable large and small ways. I would like to express thanks to Marco Martinez, for software development essential to this work and for taking this project to the next phase of development. Thanks to Matt Schultz for his electrical wizardry and advice. Thanks to Josiah Racchini for his data analysis tools. A large thank you is owed to DynaFlex, for their ongoing support. Thank you to Taylor Norman, for her phonetic analysis and general linguistics assistance. I would like also acknowledge Rod Tompkins, for his assistance moving this project beyond research.

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1. INTRODUCTION

In this document, electrical stimulation of the tongue for sensory substitution is proposed and evaluated for communication of audio information to a person. Hearing loss and existing treatments, success and limitations of sensory substitution systems, and the information throughput capability of the lingual nerve are discussed. Electrical stimulation of nerves is examined in the literature and our stimulation equipment is explained. Two studies using the equipment we developed are then described. One study was to understand the sensitivity and discrimination ability of the tongue to electrotactile stimulation in an effort to design reliable, constant intensity electrode arrays. A second goal of the first study was to determine the variability of sensitivity and discrimination ability among different people. A second study used electrode arrays designed using preliminary results from the first study and served as a preliminary feasibility test of communicating language via stimulation of the tongue. The results and their significance are then discussed.

1.1 HEARING LOSS AND TREATMENTS

Twenty percent of Americans experience hearing loss or impairment so severely that it makes communication difficult [1]. In addition to affecting quality of life, hearing impairment has been shown to be highly detrimental to an individual's standard of living. Individuals with severe hearing impairment on average make $14,100 less compared to their counterparts with less severe loss or unimpaired hearing [2]. Due to its prevalence, hearing impairment supports a $10.1 billion dollar industry [3], which provides effective treatments for many individuals with certain auditory disorders. Of existing treatment methods, there are currently two primary technologies for mitigating hearing loss or impairment. Traditional hearing aids can treat hearing loss by amplifying the intensity of some or all frequencies of an audio signal. This is often an effective treatment for those with conductive hearing loss or partial hearing loss resulting from natural aging or exposure to loud noises. Amplifying the audio signal with a hearing aid provides more energy to oscillate less responsive mechanical elements of the auditory system. Hearing aids can also work for individuals who are deaf within a certain frequency range by compressing, expanding, or otherwise mapping affected frequencies to frequency ranges within a users' hearing ability [4]. This by definition distorts the audio signal and results in a very unnatural hearing sensation for users, some of whom have difficulty adapting.

Surgical implants can be used to treat a wide range of severe hearing disorders that traditional hearing aids cannot treat. Cochlear implants, the most common type of implant available for treating auditory disorder, work by stimulating the auditory nerve in response to signals received from microphones worn on or in the ear(s). An external microphone wirelessly transmits processed audio information to a receiver located underneath the skin above the temporal bone of the skull. The receiver sends electrical signals along wires passing through the skull to an electrode array that is surgically installed inside the cochlea. The electrodes on the array stimulate auditory nerve fibers in a tonotopic manner, or stimulating at different locations along the spiral of the cochlea based on the frequency components of the sound signal. Action potentials from electrically excited neurons travel to the brain where they are perceived as sound[5]. To benefit from a cochlear implant, a user must have an intact cochlea and auditory nerve as well as functioning auditory processing ability in the central nervous system.

Hearing disorders resulting from a damaged or nonfunctioning cochlea or auditory nerve can be treated using brainstem implants. These devices function similarly to cochlear implants, but stimulate neurons in the brainstem region of the auditory pathway, often in the cochlear nucleus although other stimulation locations have also been used [6]. Though efficacy varies greatly from person to person, bypassing the outer and inner ear entirely means that brainstem implants have the potential to treat individuals with non-functioning auditory nerves, such as those with congenital diseases and tumors affecting the auditory nerve [7]. Unfortunately, due to the complexity of processing in more central regions of the auditory system and the difficulty associated with surgical installation, brainstem implants are generally not as successful as cochlear implants. This is especially evident for individuals attempting to understand spoken language using these implants.

Hearing aids and implantable devices work by augmenting signals to the auditory system or bypassing impaired sections of the auditory system. Hearing aids are relatively simple and moderately priced devices but can only effectively treat conductive hearing impairment and limited sensorineural impairment. Implantable devices, while providing a simple solution of bypassing some of the auditory system, have the unique challenge of interfacing with the central nervous system, a non-trivial engineering and surgical feat. Due to surgical expenses, the cost of these devices, which exceed $60,000 [8], can be prohibitive.

Approaches to hearing impairment that do not attempt to fix or bypass nonfunctioning subsystems, but provide the same information through other fully functional sensory systems are incredibly successful. Methods for conveyance of audio information include devices such as speech-to-text translators, and vibrotactile devices that stimulate the skin in response to audio signals. Closed captioning for television and movies is another common, highly successful form of this approach. Personal speech-to-text translators have become common due to the improved processing power of personal computers and smartphones. Likewise, improvements in speech recognition software facilitate this approach [9]. Modern speech-to-text readers provide a translation of speech reliably at greater than 90% accuracy after a delay of only seconds [10]. In the U.S. the high utilization of American Sign Language, a highly sophisticated example of nonverbal communication, and the recent improvements in speech recognition software, make non-reparative approaches to hearing impairment the most effective and widespread method of communication for the profoundly deaf and hard of hearing [11].

While highly effective, these two methods have their limitations. Speech-to-text readers are reliable and convenient, but hinder the natural flow of conversation, and cannot convey intonation. ASL allows for natural conversation and real-time “intonation” via facial expression and body language, but the language can only be used to communicate with others who also know it. Both methods are effective at conveying language information to a person, but neither method is designed to communicate other types of acoustic information such as environmental noise, or musical melodies.

Despite the limitations, non-reparative approaches to communication for hearing impairment are simple, cheap, and overwhelmingly effective. Both methods use eyesight as the alternative mechanism to convey traditionally vocal information. Eyesight is a versatile and obvious choice due to the convenience of utilizing prolific encoding schemes like written language.

While visual written and gestural language are a proven communication method used by many, Braille, a tactile written language used by many people who are blind, demonstrates that nonvocal communication is not limited to the visual system and that real time nonvocal communication could be accomplished using the sensation of touch.

Looking at the auditory system from an engineering perspective, we can generate a set of criteria that will allow us to evaluate methods capable of transmitting all the pertinent information that the human auditory system is capable of perceiving. The human cochlea has approximately 3,300 inner hair cells [12]. These hair cells transform mechanical vibrations in the cochlea into electrical nerve signals. After some limited processing, the signals are sent along the approximately 30,000 fibers of the cochlear nerve (also called the auditory nerve) to the brain [13]. Nerve fibers in the auditory nerve encode sound intensity in action potential frequency and operate over a wide dynamic range. They can fire action potentials at a maximum rate of 1 kHz when stimulated [14]. The cochlea processes audio signals and allows hair cells to communicate sound wave frequency information as low as 20 Hz. The human ear can also perceive a dynamic intensity range of 140 dB, while the dynamic range of the neural spike rate of auditory neurons is only 15-30 dB, indicating that intensity is encoded in both spikes/second and in a more complex manner such as phase, and number of excited neurons [14], though adaptation of hair cells and middle ear reflex actions also increase the dynamic range of hearing. Finally, hair cells in the human cochlea can reliably be triggered and convey signals with frequency content up to 22 kHz.

To design a method of audio information conveyance, a system presumably composed of a sensor, signal processor, transmission device, and nerve stimulator must be able to process information at a quality comparable to the human auditory system. Furthermore, a sensory organ for stimulation must be chosen with a sensing ability comparable to the cochlea.

In the brainstem and more central regions of the brain, it is difficult to find quantifiable characteristics of the sensory system that allow us to generate engineering parameters. This is due to the level of complexity of neural circuits in these regions. We hypothesize that certain qualitative features of the sensory system at these higher levels of complexity will help us generate criteria. To a large extent, the primary auditory cortex in the brain processes information in a tonotopic manner with respect to the auditory spectrum [15]. It also has a sufficient number of neurons, which can be crudely measured by cortical mass, to process this information. For a proposed sensory organ, the processing power in the brain that is dedicated to the selected system must be sufficient to handle a similar amount information that is sent to the auditory cortex. We hypothesize that a proposed system should also process information in a topographical manner. Additionally, research in cross modal activation and plasticity of sensory cortices has suggested that a sensory system that is in some way stimulated or affected by the auditory system may readily accept, integrate, and pass on information that resembles neural information coming from the lower auditory system [16][17][18]. This sensory system would not only be more readily adaptable to audio-type information, but may send information to the auditory cortex where it might be processed as regular sounds.

A systems level approach gives some quantifiable criteria and a few plausible hypotheses for choosing a method and sensory organ to sense and transmit audio information. When considering manmade components of our proposed system, practical considerations present themselves such as; method of stimulus, speed of stimulus, achievable information transfer rates of stimulus, size of device, power requirements of system, location of sensory organ, size of sensory organ, social acceptability, comfort, and ease of use.

1.2 SUCCESS AND LIMITATIONS OF SENSORY SUBSTITUTION

Engineered methods of communication for sensory system impairment are not new. Since the 1960’s the term sensory substitution has been used to describe a number of technologies that enable information to be received by one sensory organ, which would normally be received by another. Paul Bach-y-Rita, is regarded by many as a pioneer of sensory substitution technology. For fifty years he led a team of scientists and engineers who developed a number of vibrotactile and electrotactile devices that were used to transmit information to participants through somatosensory nerves in different locations on the body [19][20][21][22]. Research included the use of vibrating motors or actuators to stimulate the skin of patients. Applications of the technology included using pressure sensors in gloves to help individuals with loss of feeling in their extremities enabling the individuals to perform tasks such as writing and holding certain objects, which were previously very difficult for them to do [19].

Success was also realized in tactilely communicating more complex information in the form of images. Bach-y-Rita's early visual substitution systems utilized vibrating motors corresponding to pixels from a live camera image that were placed in a grid formation on a participant's back [22]. The resolution of these systems was poor. A simple grayscale analogy was communicated via intensity of vibration controlled by a simple duty cycle. The vibrating motors were later replaced by electrodes that electrically stimulated a touch sensation, which allowed for more compact systems with lower power requirements.

Electrotactile waveforms for neural stimulation have been studied extensively. Multiple published papers outline the best ways to simulate various mechanical sensations using biphasic current, electrical pulses [19][20][23]. Though electrotactile stimulation of the skin has been used, high voltages are required and varying moisture content of the skin due to perspiration results in inconsistent perceptions of stimuli. It was found that the tongue and oral tissues were an ideal location for electrical stimulation [24]. The high nerve density of the tongue meant that electrodes could be much smaller and more densely spaced, allowing for higher resolution on a smaller surface area. The electrical stability of the mouth was also very desirable; the relatively consistent moisture content ensures this. Furthermore, as represented in the familiar image of the homunculus, the tongue has a very large somatosensory representation in the brain, corresponding to information processing ability, rivaling that of any other body part on a per unit area basis.

Particular success has been observed using electrical stimulation of the tongue in balance rehabilitation experiments. Research in this field was aimed at developing devices to aid those with inner ear or neurological disorders affecting the sensation of balance [25][26] Using a head-mounted, 3-axis accelerometer coupled to the electrode array different regions of the tongue were stimulated in in response to tilt angles with respect to the horizontal plane. Results from these studies were compelling. Balance of participants improved drastically. Moreover, in some cases, benefits were retained even after the devices were removed. A correlation was found between the amount of training time with the devices and the duration of retained benefits. Researchers at the Techniques for biomedical engineering and complexity management – informatics, mathematics and applications – Grenoble, or TIMC-IMAG laboratory, in France developed a small wireless Tongue Display Unit (TDU) embedded in a dental retainer. In a small study, they coupled this device with pressure sensors worn in participants' shoes [25]. The pressure sensors communicated wirelessly with the in-mouth, device which stimulated the tongue similarly to the accelerometer studies described above. Though the study was small, the balance and gait of participants improved substantially when using the device.

Electrical stimulation of the tongue has been shown to be incredibly successful at communicating real time information to users at different levels of complexity. Bach-y-Rita and his team demonstrated the usefulness of the tongue to communicate complex, time dependent information to the brain [19]. Similar to their previous work, video images mapped to electrodes on the tongue enabled users to identify objects, and perform complex "hand-eye-coordination" tasks such as picking up or intercepting a moving object.

Both vibrotactile and electrotactile stimulation have been used for sensory substitution of acoustic signals. In vibrotactile studies, hearing and non-hearing individuals exhibited the ability to discriminate between vibrations of different frequencies when stimulation was applied to the hand and fingers of the participant [27][28][29]. In another study, it was observed in MRI scans of a congenitally deaf man, that his auditory cortex was activated during the vibrotactile stimulation [30].

In later research, cross-modal stimulation of somatosensory (touch) stimulation to audio processing structures of the brain was found in individuals with normal hearing ability, suggesting that vibroctactile stimulation could be used as an alternative to auditory input for both congenitally and recently deaf individuals [31]. In this study, researchers provided bursts of vibrotactile stimuli to the participants' palms and fingers while live fMRI brain scans were observed to identify regions of the brain activated during the stimulus. Similarly, brain scans were performed while bursts of audio stimuli were provided to the individual. An 85 mm^3 section of the posterior auditory belt area of the brain was found to be activated by both audio stimuli and vibrotactile stimuli. Their results support the use of somatosensory substitution for hearing loss and may even suggest shorter learning times compared with other sensory substitution methods.

In studies involving direct sensing of electrical signals in neuron clusters of a monkey brain using surgically implanted tungsten microelectrodes, researchers found that 72% of the sites tested inside the brain that were audio-responsive, were also responsive to some type of somatosensory stimulus [32].

It is no surprise that audio-to-tactile communication devices known as tactile vocoders have been successfully implemented in a number of different ways. Simple vibratory vocoders worn on the arm enabled study participants to learn a vocabulary of up to 150 words in a as little as 50 hours [29]. Subsequent studies involving artificially deafened participants achieved a vocabulary of 250 words in 80 hours [33]. Fingertip tactile display methods have also realized limited success at supplementing lip-reading [34][28].

A number of studies involving both children and adults who were profoundly deaf have shown that limited training with both electrotactile and vibrotactile sensory supplementation devices aids significantly in sound and word recognition tasks as well as narrative tracking [35][36][37][38]. In these studies, gains of 20-50% over aided hearing (using hearing aids) alone in tests for word recognition and narrative tracking were common when tactile aids were combined with aided hearing or lip reading. Similar gains were common on tests involving new words, which were tactually unfamiliar to the participant. Some participants scored more than 100% better than aided hearing alone on new word identification tests when aided hearing and tactile aid were combined [37].

Despite the supporting neuroscience research and previous success of vibrotactile and electrotactile vocoders, and the success of the tongue at communicating complex, time dependent information, there has been surprisingly little interest in using the tongue to convey audio information to the brain. In one of the few studies on the subject, the tongue was evaluated in a limited scope to communicate phoneme information to the brain to supplement lip reading [39]. While successful at demonstrating the usefulness of tongue stimulation to supplement lip reading, the study yielded limited results due to its short duration and lack of training for participants. The scope of audio-tactile encoding schemes that were tested was also highly restrictive. An extensive study has been performed by researchers in Ireland on the effects of audio-lingual sensory substitution to treat tinnitus (constant ringing of the ears). The clinical study showed significant reduction in tinnitus for subjects who participated in the 16 week trial [40]. The methods and equipment used in this study stimulated the tongue in response to audio information in similar way to the studies performed by others and the studies proposed by ourselves. Although the focus of the study was on tinnitus treatment, the results show that the effects of long term training with audio-lingual sensory substitution are compelling.

The limited success of audio-lingual tactile vocoders is likely due to the restricted amount of information sent to the tongue and the time constraints in these studies. Lack of success is likely not due to any bandwidth limitations of the tongue itself. For example in the lip reading studies, a minimal information whole phoneme encoding scheme was chosen to minimize learning time, and training was limited to a single 90 minute session [39]. With much longer training times it is likely that participants would become as proficient at interpreting sounds conveyed to the tongue as Braille Readers are to interpreting fingertip touch sensations to written language.

1.3 COMPARISON OF DATA TRANSFER RATES OF THE AUDITORY AND LINGUAL NERVE

A lingual system capable of transmitting useful information to a person such that conversation can occur would necessarily be required to have a higher information transfer rate than has been utilized previously. Braille, a tactile communication method capable of transmitting useful language information through the somatosensory system typically takes four months or more to learn [41]. A high bandwidth system capable of stimulating the tongue with a similar amount of information as is sent to the ear would likewise require a similar period of training.

We believe that the ability of the tongue to send audio information to the brain via the lingual nerve is limited by the ability of engineered solutions to stimulate the full dynamic range of as many mechanoreceptors as possible. As the information transfer capability is thus limited by electronic devices, it becomes convenient to express audio and stimulus quality in terms of information theory, which for our purposes can be reduced to a simple bitrate of information that can be reliably transmitted through the tongue. The telecom standard is to sample and transmit audio between users at 64,000 bits/s (bps) or baud which is equivalent to 8000, 8-bit samples per second [42]. Proprietary vocoders used by the military can transmit recognizable language at rates as low 600 bps [43]. Both of these methods allow users to understand language with no additional training. If additional training is acceptable to a user, English phonetic information at conversational speeds can be transmitted at rates as low as 110 bps [44]. Using these existing information encoding methods, stimulators on the tongue must reliably transmit audio information to lingual nerves at rates somewhere between 110 and 64,000 baud.

Although the tongue can likely handle information transfer rates comparable to the ear, well above the telecom standard of 64,000 bps, a good first step toward achieving this is to utilize existing tactile stimulation methods that have been successful at communicating information to a person. There is general agreement that for varied encoding methods, the throughput of a single electrode on the skin is between 2-5 bits/second [45][46][47][48]. Novich and Eagleman recently published a study in which a 3x3 array of vibrotactile stimulators was able to communicate at most 37 bps, or 4 bps/stimulator, of information to a person using a variety of stimuli. Results from this study suggest that the throughput capacity of a stimulator can be expanded to an array of stimulators by nearly an order of magnitude [44]. By our calculations, explained in succeeding paragraphs, simpler encoding schemes such as Braille, which uses six binary stimulation points, yield tactile throughput capacity at greater than 7.5 bps for each stimulation point after 4 months of training.

As we have suggested above, the lingual nerve might be able to transfer information to the brain at a rate comparable to the auditory nerve, and the somatosensory cortex in the brain that is dedicated to processing information from the tongue is sufficiently large to handle complex information. We assume that the expandability of a single stimulus suggested by Szeto's group and by Novich and Eagleman's work can be further expanded past 9 electrodes based on the information transfer capability of the lingual nerve, and our assumptions about the information processing power of the somatosensory cortex. The total possible throughput of the tongue can thus be estimated based on the number of electrodes that can be fit on the tongue.

To reliably induce the full 2-5 bits/s of stimulus on each electrode, we must account for the receptive fields of the tongue. Furthermore, any complicating factors resulting from electrical stimulus must also be addressed. Maeyama and Plattig tested the two-point discrimination ability of the dorsal surface of the tongue to an electrical stimulus and found it to vary greatly by location [49]. In four locations on the tongue, which we assume bound an area roughly 4cm by 4cm, the minimum two point discrimination distance varied greatly. By performing a linear interpolation of the four points tested over a 40mm by 40mm grid, we can estimate the minimum distinguishable electrode spacing across a large surface of the tongue. From this, the maximal number of electrodes that can be placed on the tongue ensuring distinct sensation from each electrode is estimated to be about 109 electrodes. Assuming that the expandability of electrodes holds for another order of magnitude, as it did for Novich and Eagleman's work, the total throughput of mechanoreceptors on a 4cm by 4cm area of the tongue using existing stimulation methods and encoding schemes is between 200 and 545 bits per second, within the baud rate of intelligible language encoding methods.

Supporting this hypothesis, the work of Novich and Eaglman suggests that the total throughput of the dermis of the entire torso, roughly a $3500cm^2$ area, is between 600 and 900 bps. Scaling this throughput to the ratio of the average required area for a single electrode on the torso and on the tongue (determined by average two point discrimination distances) gives an estimated throughput for a 4cm by 4cm area of the tongue at 558-860 bps, or about 93% of the total throughput of the entire torso.

While Novich and Eagleman used metrics that should not be affected by encoding scheme or amount of training to determine the throughput of the back, it has been observed that two-point discrimination ability changes with increased training [50]. Reading rate studies of experienced Braille readers may help provide a more accurate estimation for the achievable throughput of the tongue for users with a high level of training. Some estimates put the effective baud rate of experienced Braille readers at about 25 bps [51]. This metric is somewhat flawed for our purposes. Braille is a written language composed of characters which contain 6 binary dots. MNREAD tests adapted to Braille put the reading rate of experienced readers at a median of 7.5 characters per second, while some users read as fast as 14.4 characters per second [52]. As each character contains 6 bits of information, this puts the information transfer rate for experienced users at 45-86 bits per second. Each of these characters is “written” on a $34.5mm^2$ area [53]. Scaling the information transfer rate of the finger per unit area via Braille by the ratio of the required area for a single stimulus of the finger and the tongue and assuming expandability [54][49], Braille reading studies for the fingertip suggest that the information transfer rate for stimulus on the tongue could be between 958 and 1831 bps for experienced users.

Our estimations of achievable throughput of the tongue are highly dependent on the non-trivial assumption that achievable baud rate of a single electrode is linearly expandable over two orders of magnitude. The work by Novich and Eagleman suggest that the baud rate estimation is linearly expandable over a single order of magnitude to about 10 stimulators. It is currently not proven that this linearity continues to a larger number of electrodes, however, based on a crude analysis of the anatomy of a neural signal from the ear and the tongue, we believe that there is no theoretical limitation to sending information through the lingual nerve at a quality comparable to that perceived by the auditory system. To explain, trained human ears can distinguish between music recorded at 44,000 Hz with a 10-bit sampling resolution, and audio recorded at lower quality, thus a rough estimation of the throughput of the auditory nerve is 440,000 baud. Based on calculations made in the following paragraphs, the auditory and lingual nerves can transmit action potentials at a similar maximum rate, and the dynamic range of a single neuron in each system is similar. Thus, we believe that the theoretical baud rate of the tongue and lingual nerve exceeds any baud rate we can achieve currently with electrodes.

We suggest that the lingual nerve of the tongue is capable of receiving and transferring auditory information to the brain at a quality similar to the auditory nerve. In fact, the information transfer capabilities of mechanoreceptors on the anterior 2/3's of the tongue may exceed that of the auditory nerve, as explained in subsequent paragraphs.

Information in both the auditory and lingual somatosensory system is in its simplest form when encoded into action potentials in their respective nerves. It is difficult to compare the "amount of information" in two physical properties that each system senses, and equally difficult to compare the way in which the brain processes information from each system. However, information in both sensory systems briefly takes the same simple form of digital patterns of action potentials in the auditory and lingual nerve. The only point at which the information takes a simple enough form in the nervous system to compare is in the digital signal of the nerve between the sensory organ and the brain.

Information in the human auditory nerve is coded spatially and temporally. Sound information in the frequency range of human speech is coded somewhat differently than other ranges, and there is likely both spatial and temporal coding of sound intensity for all frequency ranges [14]. However, in a simplified view of the system, frequency or tone is coded spatially, and sound intensity at a given frequency is coded primarily by the frequency of action potentials. The rate of information transfer in both the auditory and lingual somatosensory system is limited by the number of sensory cells in each system, the maximum frequency at which sensory cells in those systems can transduce mechanical stimuli to electrical signals and by the number of synapses present between the periphery and sensory cortex. The maximum spiking frequency of an axon in either of these systems is limited by the absolute refractory period of a neuron.

While the number of nerve fibers in each nerve may seem like a good indication of the information transfer capabilities of the system, redundancy in the auditory nerve [55] and uncertainty about the percentage of afferent and efferent fibers in the lingual nerve suggest that a simple fiber count is a poor metric of information transfer capabilities[12][13][56]. The action potential conduction velocity in each nerve bundle, while affecting signal latency, has no effect on the actual information transfer rate of the system. Furthermore, the action potential conduction velocity of both the auditory and mechanosensory lingual nerves are similar, though the lingual nerve conduction velocity is on average faster [12] [13] [56][57][58]. The longer transmission distance to the brain in the lingual nerve has an effect on signal latency, but this effect is partially mitigated by larger fiber diameter and faster conduction velocities in the lingual nerve.

Information in both the auditory and somatosensory system is coded by location of stimulus and action potential frequency. Thus the total amount of information that can be transferred by either nerve bundle can be approximated with a crude metric of action potentials per second. This metric, shown in equation 1, can be used to compare the information transfer capabilities of the auditory and lingual nerve fibers. The metric is calculated by taking the total number of unique signals in the lingual and auditory nerve, divided by the refractory period of the transmitting cell.

$$\frac{AP}{Sec} = \frac{Sensory\ cells}{Limiting\ Absolute\ Refractory\ Period}$$

Equation 1: Maximum Action potentials per second for a nerve bundle

In the auditory system, roughly 3,300 inner hair cells release neurotransmitters to 30,000 myelinated nerve fibers in the auditory nerve [12] [13]. This averages to about 10 nerve fibers per hair cell. The refractory period of these fibers is 0.8ms [55]. There is no effective refractory period for the inner hair cells, which release neurotransmitter to the neurons, however they can adapt, affecting the rate of signaling. Synapse time affecting transmission latency is approximately 0.7-0.8ms [59]. Thus the maximum number of action potentials per second that the auditory nerve is capable of sending is about 4.2 million.

Similarly, information transfer rates for somatosensation in the tongue can also be expressed. The lingual branch of the trigeminal mandibular nerve carries somatosensory information from the anterior 2/3's of the tongue. This nerve also carries some efferent information to glands, but it is generally accepted that the nerve mostly contains somatosensory afferents [56]. There is great variability in the number of lingual nerve fibers in humans. Counts range from 10,633 to 33,279 myelinated nerve fibers with a mean of 16,868 [56]. Each of these nerve fibers innervates a region in the front 2/3's of the tongue. Fiber diameter distributions in the total myelinated fiber count (TMFC) suggests that at least half of the fibers in the lingual nerve are mechanoreceptors in the tongue [56]. This puts the total mechanoreceptor count, in the tongues of subjects in this study, at greater than 5,000 or 16,000 depending on the subject.

Although there are multiple types of mechanoreceptors in the tongue, each with different structure and refractory periods, the exact ratio of these mechanoreceptors in the tongue is unknown. The range of refractory period of neurons that transmit somatosensory information in the human body is known to vary from 0.7 to 3.5ms [60]. Using the mean lingual nerve fiber count of 16,868, and assuming that 70% of these nerve fibers are from mechanoreceptors, and using the most conservative refractory period for these receptors from the literature, we calculate that the average maximum action potentials per second for the lingual nerve in a normal human is 3.3 million, or 78% of the information transfer capability of the auditory nerve. Less conservative estimates put the information transfer capability at 43 million action potentials per second, well above the information transfer capabilities of the auditory nerve. The large range of this estimate is due to the high variability of nerve fiber counts in humans, the uncertainty about the percentage of mechanoreceptors afferents in the lingual nerve, and our uncertainty about the number of each type of mechanoreceptor in the tongue and their refractory periods.

To compare the information transfer capabilities of the auditory nerve and the lingual nerve, we made several assumptions. These assumptions include: 1) the information transfer capability of a peripheral nerve is only dependent on the number and frequency of unique action potentials in a system 2) there is a similar signal-to-noise ratio for the auditory and lingual nerve, 3) the signal latency of both systems is small and unimportant, 4) that only mechanoreceptors on the anterior 2/3's of the tongue are relevant, 5) adaptation and other types of neuronal change is not considered and 6) we analyze the system over a short period of time in which we assume the system to be static. In addition, this analysis does not consider more central pathways or the information processing ability of the lingual somatosensory and primary auditory cortex.

Although our metric is crude, it provides valuable insight on a few key points. Most importantly, if the full capabilities of mechanoreceptors on the anterior 2/3's of the tongue can be leveraged, the lingual nerve can transmit audio information to the brain at a level of complexity comparable to that of the auditory nerve. Further supporting our hypothesis, it has been calculated that mechanoreceptors in the skin only have a dynamic range of about 10 dB [48]. Using electrical stimulation, the dynamic range of the tongue has been found to be 17dB [61]. This may seem problematic being that the auditory system has a dynamic range of 140 dB [15]. However the dynamic range of a single auditory neuron is only 15-30 dB [14]. Spatial and temporal coding, as well as adaption mechanisms are used in the auditory system to increase the dynamic range by an order of magnitude. The first two techniques can be used for stimulating mechanoreceptors on the tongue. Adaption mechanisms in the auditory system, and amplification functions of the outer hair cells can be simulated electronically with audio processing techniques, the description of which is outside the scope of this thesis.

Based on Braille learning studies that show expansion of the sensorimotor cortical representation for the Braille reading finger, and the cross modal activity between the somatosensory system and auditory system, we believe that, with time and training, the brain will be able to decode and process audio information sent to it through the lingual nerve as is supported in the literature [62][63][64][32][31][65].

Given that maximum action potential transfer rates in the auditory and lingual nerve are similar, and the ear is capable of information transfer rates which are orders of magnitude greater than we are attempting, we believe that our assumption of linear expandability of electrode transfer rates within our scope is reasonable. Thus, the total achievable information transfer rate of the tongue using our methods is dependent on the number of electrodes that can be placed on the tongue. In lieu of any high resolution data available on the two-point discrimination ability across the surface of the tongue, our estimates used 1,596 estimated minimum discrimination values interpolated from Maeyama and Plattig's four data points and gave us an achievable transfer rate between 200 and 1,800 baud. These estimates, though useful as a preliminary estimate of the tongues throughput, are highly uncertain. Data for other measurements of electrotactile sensitivity on the tongue is available over a larger area of the tongue [66], but the characteristics measured in these studies do not necessarily correlate to discrimination ability.

To better understand the achievable throughput of the dorsal surface of the tongue, two experiments were proposed. The first proposed study, to provide high resolution two-point discrimination data in two directions for electrotactile stimuli on the surface of the tongue, and the second, a preliminary test to evaluate the feasibility of sending information at high bitrates to the brain via the tongue. To test these two hypothesis two devices were developed.

2. DEVELOPMENT OF A LINGUAL NEURAL STIMULATION DEVICE

The lingual stimulation devices developed to test our hypothesis operate on the same principals of designs used successfully by others. This section will cover the design of our two types of tongue neural stimulation device, starting with the theory of electrical nerve stimulation, and summarizing the designs of two stimulation devices that are used in the experiments. Much of the theory discussed in this section is based on stimulation of the neurons from surface electrodes placed on the skin. The same principles apply to stimulation of neurons in lingual tissue.

2.1 MODEL OF SURFACE ELECTRODE NEURAL STIMULATION

It has been found that a current source applied extracutaneously can initiate current flow through ionic channels in an axon membrane causing a voltage change across the membrane and initiation and propagation of an action potential. As explained in the literature, this process can be used to model electrical stimulation of both myelinated and un-myelinated axons [67]. Neurons can be stimulated using 1) a monopolar stimulus, where there is one stimulation electrode and the return-current-electrode is located far enough from the first electrode that it's electric field does not affect the propagation of action potentials produced from the stimulus electrode, or 2) a multipolar stimulus, where local electrical currents travel a short distance through tissue between two or more electrodes. In monopolar and multi-polar electrocutaneous stimulation, electrodes are used to create an electric field in tissue that causes ions to migrate toward or away from the electrode resulting in an ionic current. Ions move through extracellular space, as well as through ion channels in cell membranes. The voltage and current density in the tissue is largest closest to an electrode, and decreases in magnitude in tissue farther from the interface.

In both monopolar and multi-polar stimulation, electrons flow through the skin [68] and through the skin electrode interface, but because of tissue resistance a voltage potential is maintained and an electric field is set up between electrodes[67][69]. Constant current controlled pulses are used for skin stimulation due to nonlinear skin resistance. The electric field causes ionic current to flow through tissue and axons between electrodes [70]. It has been suggested that myelinated A-β fibers are the dominant mechanism of transmission to the brain for electrotactile stimuli [71]. Current flowing to an electrode is due to ion/electron movement through tissue and through a single, or a few nodes of Ranvier on a myelinated axon [70]. In a common model of electrocutaneous stimulation, a single Node of Ranvier on a myelinated axon is closest to the active electrode and thus is in the most intense electric field. Ions flow through this node (node 'n') toward the electrode. In most models, the Frankenhauser-Huxely model is used for node n, and a passive model (subthreshold) is used for all surrounding nodes. [70][71][72]. Axoplasm has a lower resistance than the tissue around it and an axon acts as a passive cable load, shunting a portion of stimulus current flowing through tissue toward the electrode [71]. Ions flow through the axon towards node 'n' and out this node towards the electrode. Ions also flow into or out of the axon at other nodes according to their location in the electric field. At node 'n' ionic flow through ion channels reduces the electric potential of the inside of the membrane relative to the outside due to charge accumulation in the area near the electrode. Once the threshold potential is reached and voltage-gated sodium channels open in the cell membrane, resulting in an action potential initiation and propagation in both directions.

Depolarization of a neuron by an electrotactile stimulus leading to a perceived sensation is predominantly due to sodium current though the cell membrane [71]. Both positive and negative electrocutaneous current pulses can initiate an action potential in an axon. Mathematically, this is explained by the pair of values found by solving the Frankenhauser-Huxely model in Butikofer and Lawrence's calculations [71]. This is supported by experimental evidence in the literature and by a similar model by Rattay [67][69].

2.2 PRACTICAL DESIGN CONSIDERATIONS

Tissue irritation can be caused by ionic charge accumulation in tissue underneath an electrode causing an electrolytic effect which can damage cells. To minimize tissue irritation, the charge transfer per pulse on an electrode should be limited and the average charge transfer during stimulus should be zero [71]. To achieve this, biphasic current pulses are often used.

Biphasic current pulses both restore membrane potential immediately after stimulation and reduce tissue irritation and electrolytic effects by restoring skin potential to zero in a local area [72]. It has been found that to minimize heating effects, the interval between positive and negative phases of a biphasic current pulse should be zero [72]. Biphasic pulses allow for multiple pulses to be used in rapid succession to achieve a summative depolarization effect with lower energy depolarization compared to monophasic pulses, especially in tissue with nonlinear resistance. The majority of the summative depolarization effect can be realized with three pulses[72]. Using multiple pulses decreases threshold charge per pulse and increases the dynamic range of stimulus. Alternatively, in monophasic pulses, the skin resistance changes as charge accumulates during subsequent pulses and the voltage of stimulus must be increased to maintain the same current.

Coupling capacitors can be used with monophasic pulses to approximate a biphasic stimulus, but non-linear skin resistance makes this imperfect for skin [72]. Tongue tissue and saliva have nearly constant resistance, so voltage control and coupling capacitors approximate a biphasic current pulse well enough. This does not perfectly control current though, and slight nonlinearity in tongue tissue resistance results in a very small net dc current. In studies involving hundreds of participants at the TCNL, none have reported tongue irritation using this method [24].

Although electrical stimulation of nerve fibers has been studied extensively and nerves can be stimulated using a variety of techniques, the Tactile Communication and Neurorehabilitation Laboratory (TCNL) group are experts on electrotactile stimulation of the tongue, and it was decided that features of their successful methods would be the used in our device. Notably, we decided to stimulate nerves using bursts of capacitive-coupled, positive pulses to depolarize the nerve membrane. A similar pulse waveform on each electrode, and similar waveform parameters were used as described By Kaczmarek [24].

2.3 CTHULHU DESIGN

Our studies required a method and apparatus to stimulate the tongue to both test electrotactile sensitivity and discrimination ability. Successful work on information communication using tongue stimulus has been performed by the TCNL at the University of Wisconsin Madison. Thus, our stimulation methods and devices borrow heavily on designs and methods published by this group, and in particular K.A. Kaczmarek.

Two tongue stimulation devices, shown in Figures 1 and Figure 2, were used to generate electrical pulses on an electrode array to stimulate the nerves on the surface of the tongue for sensitivity and discrimination studies. These devices are based on designs published by Kaczmarek [24] and use an RC network similar to Kaczmarek's device so that very little net charge flows through the tongue. Certain features of Kaczmareks's devices were not needed for our studies and the devices were modified from his original designs to use fewer components. Our experiment differs from previous experimental designs [66] in that we used 5-volt pulse amplitude for all stimulation. Our devices were constructed in a simple modular manner, which allowed an arbitrary number of modules (shown in figure 3), to be connected on a single communication line. This allows a user to add any number of modules to increase electrode count without modification to existing hardware and software. Two cosmetically different devices were used in our studies. The first device, called the "Tickler" consisted of 6 modules with 18 electrodes each to achieve a total of 100 electrodes (8 electrodes on module number 6 were not used). The second device, which we named the "Cthulhu", was a more mechanically robust version that consisted of 3 interlocking modules each with 36 electrodes (again, 8 electrodes were not used on the 3rd module). An RC network was used to achieve a similar transient current through the tongue during stimulation.

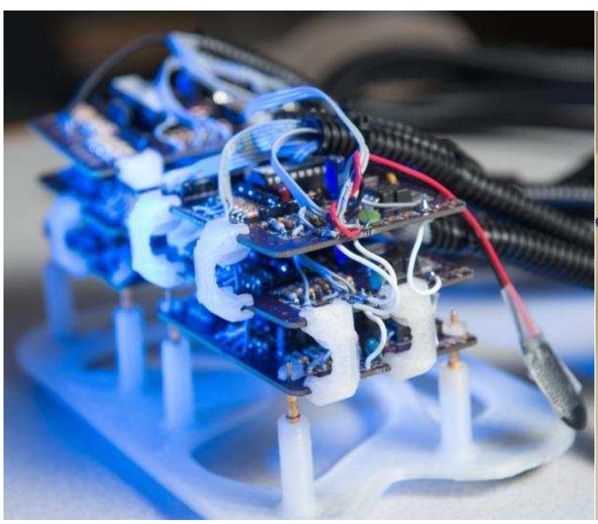


Figure 1: The "Tickler", a constant voltage Tongue Display Unit used in this study.

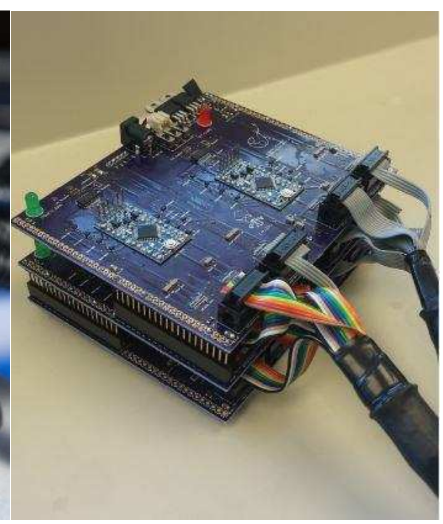


Figure 2: The "Cthulhu", A variable voltage Tongue Display Unit used in this study.

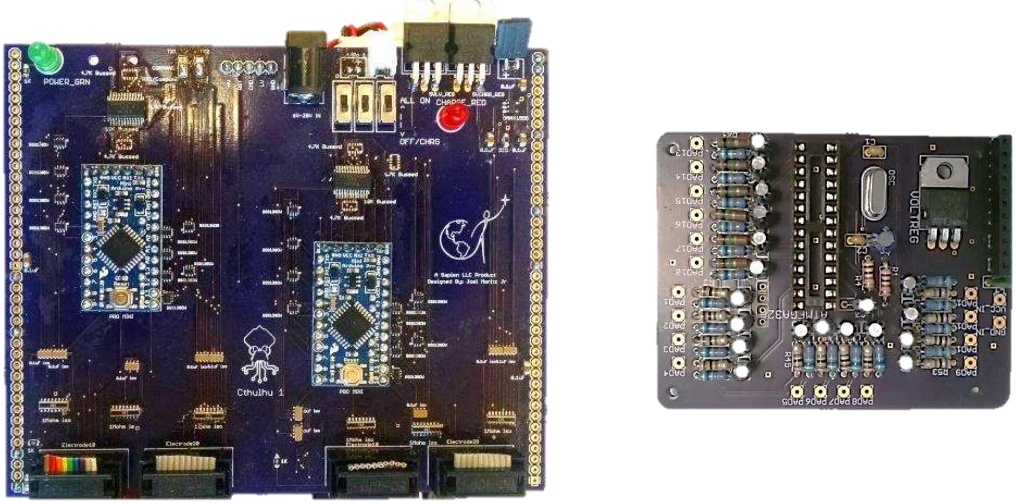


Figure 3: A Cthulhu (left) and Tickler (right) stimulation module. Multiple modules of either design may be connected together to make devices with any desired number of electrodes.

The Cthulhu series of prototype device were constructed with the intent of using them to map the electrotactile sensitivity and discrimination ability of the tongue. Studies were to involve at least 20 participants in multiple tongue-mapping sessions lasting approximately one hour. Comfort, sanitation, and safety were important design considerations.

Mouthpieces needed to be designed to map sensitivity and discrimination ability of a 40x40mm area of the tongue with 2mm resolution. A total of 400 electrode locations were required to map the area. For health and safety considerations, each participant was given their own mouthpiece that could be disposed of at the end of the study. Cost and size considerations prevented us from designing an electrode array with 400 individual electrodes, connector size and weight also prevented this. Arrays with 100 electrodes and connectors were designed that could be indexed to 4 discreet positions in the mouth to achieve the 400 electrode, 40x40mm desired mapping area. The array could be made from simple 2-layer FR-4 circuit board material with gold plated copper pads and connectors.

To index the array in the mouth, four rows of two holes were designed into the middle of the board. A sliding bite pad with small bumps was indexed along the array by sliding it until the bumps slid into the holes in the PCB. This allowed electrode arrays to be positioned in 4 different (anterior to posterior) regions. Bite pads were manufactured as needed on an FDM 3d printer from ABS plastic.

Electrode arrays were made from simple 2 layer printed circuit boards designed in EAGLE PCB design software. Electrodes were gold plated vias with an outer diameter of 1.02mm and an annular ring thickness of 0.06mm.The electrodes were positioned in a 5x20 rectangular array with 2mm center-center spacing (approx. 1mm edge to edge). The arrays were designed to be inexpensive and disposable so that each participant could use their own personal electrode array. The PCB arrays were plugged into 2 card slot connectors at the end of cables attached to the outputs of the devices shown in Figure 4. The electrode array itself was a rectangle 1cm by 4cm. To map a 4cm square of the tongue, the array was indexed farther into the mouth by sliding the stop pad shown in Figure 5 to snap in positions along the array spaced 1cm apart. An illustration of this is shown in Figure 6. The participant would lightly press the top of their tongue against the array, and the front of their tongue against the back of their bottom incisors. This provided a reliable method to position the tongue appropriately on the mouthpiece.

Figure 4: A mouthpiece, bitepad (underneath) and connectors.

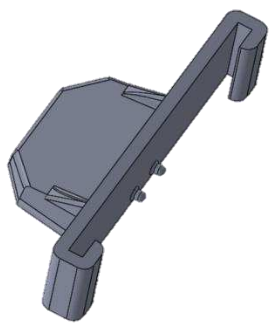


Figure 5: A stop pad used to positively locate array in the mouth. The large plate is placed between lips and teeth while the arms wrap around and grip edges of PCB array. The two pins lock the pad into place at any of the four positions on array.

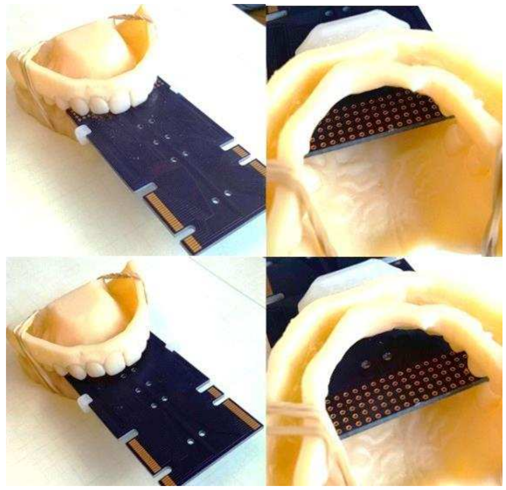


Figure 6: Two of four possible configurations for electrode array showing external appearance, and in-mouth location of electrodes that will contact the tongue.

A simple text via serial terminal was used to interface with the Cthulhu type devices. As illustrated in the block diagram in Figure 7, Module-0 on each device would receive text commands from the computer and send subsequent text commands to the computer and modules 1-5. Text commands were used to activate electrodes, and change certain settings on the device. Initially during studies, all commands to control electrodes were manually entered by the researcher. It was quickly discovered that this was inefficient and resulted in study sessions exceeding 2 hours. Thus, four, 116 electrode pair sequences were hard-coded into the devices for the 4 locations that the arrays were indexed to on the tongue. Single key commands enable the operator to index through these active pairs at will, shortening average study durations to less than one hour.

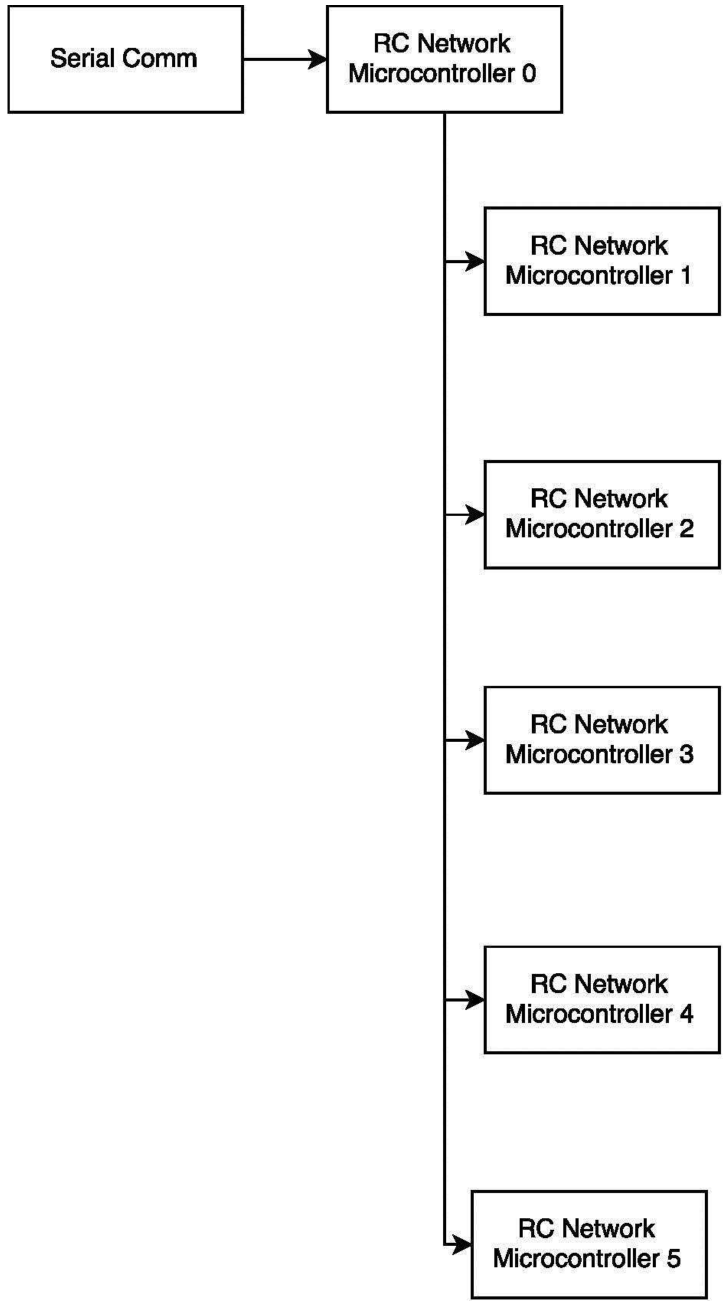


Figure 7: Block Diagram for the Cthulhu device. Microcontroller 0 receives input from computer, and sends instructions to five other microntrollers.

Firmware updates on the Cthulhu series could be accomplished in one of two ways depending on the version of the device. On the older model, DIP chips could be removed from sockets on each module and programmed individually, then placed back in their modules. On the newer model, male pins on each module allowed access to the programming port of each microcontroller. Each module could be programmed individually with an FTDI programmer.

The microcontroller output to the RC electrode network is a waveform consisting of short bursts of pulses inside larger bursts of these bursts described in more detail in succeeding paragraphs and shown in Figure 8. For a single module consisting of 18 channels, the bursts are staggered so that only one of the 18 electrodes is active at a time. This has been shown to improve the localization of sensations produced when multiple electrodes are active [73]. It should be noted that although only one electrode may be pulsed at a time when multiple electrodes are activated, the participant experiences simultaneous sensations on active electrodes due to the small time scales of stimulation. Software for our devices is set up so that no two modules are simultaneously active during stimulation. A typical waveform for a single module (when not in contact with the tongue) is shown in Figure 8. Parameters shown in the figure can be adjusted to produce a range of sensations and intensities. In our study, we maintained a constant value of 5 volts for the pulse amplitude (PA), an outer burst period (OBP) of 36ms, an inner burst number (IBN) of 3, a peak to peak (PP) length of 10µs, and an inner burst period (IBP) of 150µs. Pulse width (PW), and outer burst number (OBN) have been found to correlate to perceived intensity and comfort [19]. In previous unpublished studies, we found that we could reliably change the noticeability or intensity of a stimulus by coupling these two parameters and simultaneously incrementing their values from 3 to 9. This gave us 7 distinct intensity settings. At the beginning of each experiment, participants selected their preferred intensity setting, which was maintained for all stimuli throughout the duration of the experiment. PW and OBN coupled settings are referred to as “intensity” or “noticeability” levels throughout this manuscript.

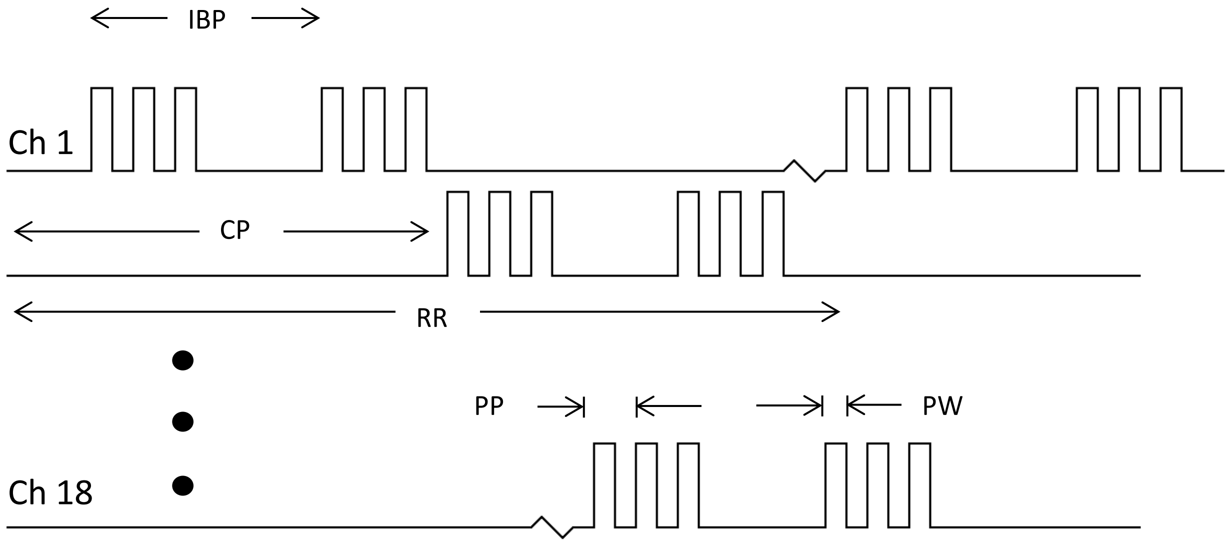


Figure 8: A chart of microcontroller output waveforms for each channel and variable parameters adapted from Kaczmarek [24].

The desired output on each active electrode of the Cthulhu device when electrodes were in contact with the tongue was a biphasic current pulse train resulting in a very small net charge transfer, and residual surface potential. The equivalent circuit of a single active electrode on the Cthulhu device was modeled in Simulink and is shown in Figure 9. An electrode in contact with the tongue can be modeled as a resistor in parallel with a capacitor, we measured the contact resistance to be approximately 300 ohms and estimated a contact capacitance of 0.5nF based on similar work[24]. The estimated contact resistance of our electrodes is significantly different from the electrode resistance of the TDU [24]. This is due to saliva being the primary electrical pathway in our device from electrode to tongue due to the circuit-board-via design of the electrodes. Our array design holds saliva in the small plated hole in the via due to capillary action. The measured resistance of the tissue itself, independent of contact resistance, was very small and is considered negligible in our model. This is consistent with other models in the literature [24].

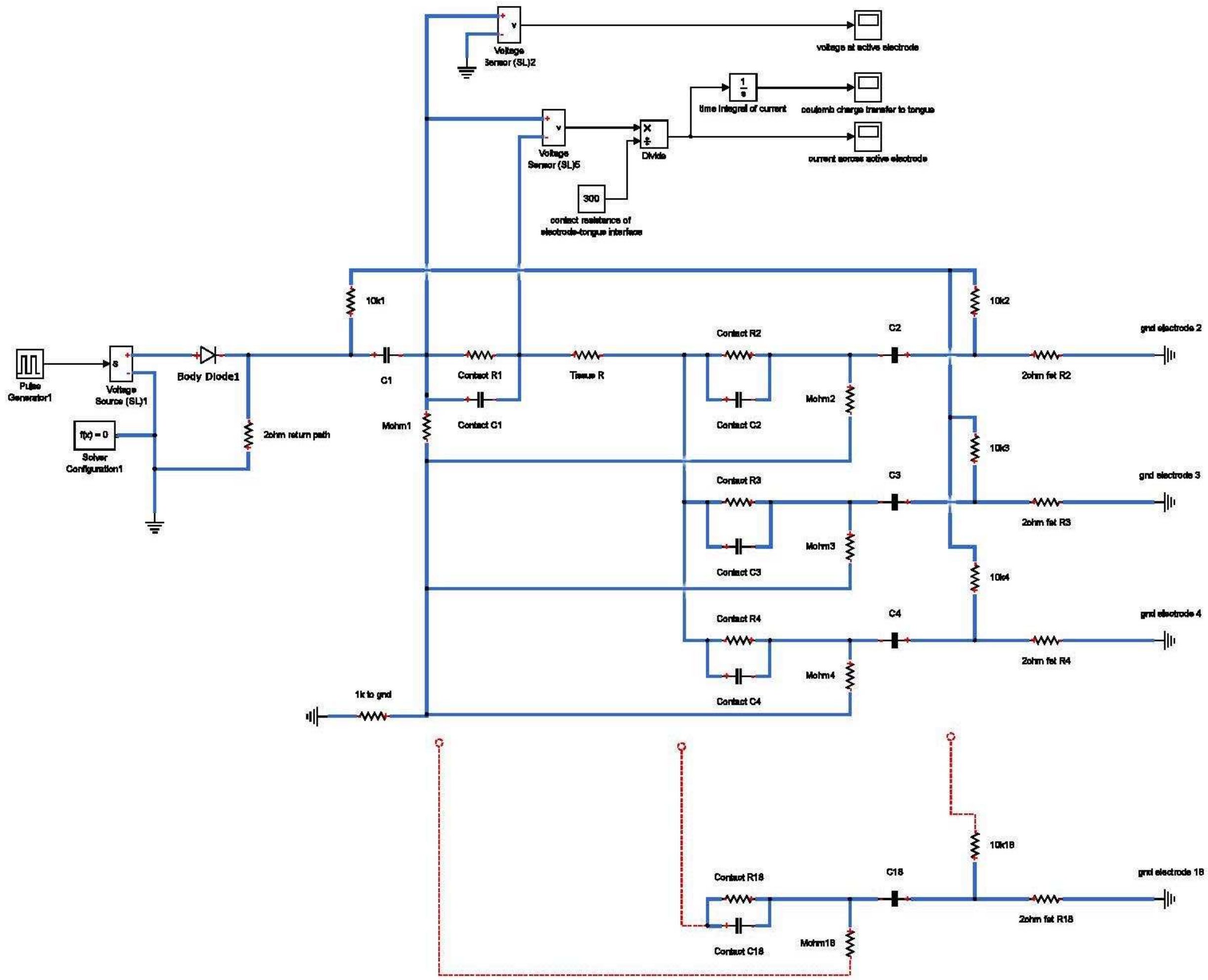


Figure 9: Equivalent circuit for one module on the Cthulhu device modeled in Simulink. Six modules make up the Cthulhu device, four with 18 electrodes, and two with fourteen electrodes. A model incorporating all six modules was used in our analysis.

Six modules make up the Cthulhu device, four with 18 electrodes, and two with fourteen electrodes. A model incorporating all six modules was used in our analysis. The Cthulhu device was designed with higher voltage capabilities that were not used in studies described in this thesis. The n-channel mosfets and 10KΩ used to boost voltage had no purpose in our studies, and had little effect on our circuit, but were included in our model for completeness. A 5 Volt pulse through the body diode of the n-channel transistors we used is modeled by the Pulse generator, voltage supply, and diode. The return path for current when the active electrode becomes inactive is modeled by the 2Ω resistor. Since our voltage supply in the model is ideal, the low resistance in parallel with the rest of the circuit has no on current and voltage delivered to the rest of the system. Monitors are located at the top of the model. Contact R's in the model were 300Ω. Contact C's were 0.5 nF. Tissue resistance is considered negligible and was modeled as 0Ω. The on-resistance of our n-channel mosfet was 2Ω, and is modeled by the "2ohm fet R's" in the model. 1 MΩ resistors maintain a stable DC operating point on the surface of the tongue, but have little effect on the circuit. The "1k to gnd' resistor provides a convenient place to measure current during operation, but was not used. 10KΩ resistors are used for variable voltage functionality that was not used in our studies. These resistors had minimal effect on the circuit.

From our model, it was calculated that after approximately 70μs for a single pulse, the residual charge accumulation on the tongue at the electrode interface is less than 10nC as shown in Figure 10. The modeled electrode tongue interface potential is also shown in Figure 11 (left) along with the measured electrode interface potential (right). For a single pulse, the potential at the electrode tongue interface dissipates quickly due to capacitive coupling as well as stabilizing resistors. The rapid dissipation of local charge and electric potential was designed into our system to prevent tissue irritation during stimulation. While there is a small net charge accumulation due to rapid pulses during an inner burst in our system, charge is dissipated from the interface area after the completion of an inner burst when the electrode becomes inactive for 120 microseconds.

During stimulation of a participants tongue, voltage measurements were taken at the active electrode using a Rigol DS1054Z oscilloscope. Measured outputs were similar to modeled outputs as can be seen in Figure 11. Measured voltages decayed at a similar rate compared to modeled voltages, indicating an accurate estimate of the electrode-tongue interface resistance. A small transient voltage spike was observed in the measured output at the beginning of positive and negative pulses that was not observed in the modeled output. This is likely due a larger actual contact capacitance than modeled but does not affect stimulus in any significant way. The small charge accumulation during rapid pulses has no electrolytic or otherwise damaging effects as the charge is dissipated quickly after an inner burst. Future designs may use altered pulse timing or circuitry that dissipates residual charge within an inner burst.

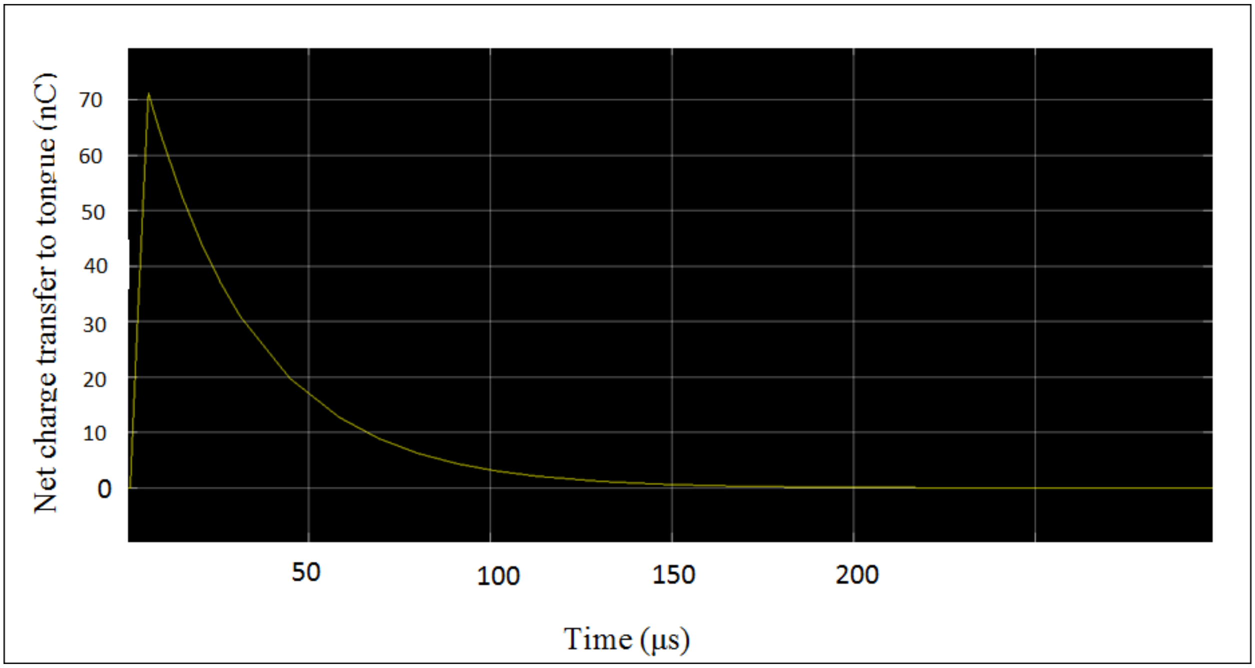


Figure 10: Coulomb charge transferred to tongue for a single pulse. Approximately 70 µs after pulse initiation, the net charge transfer to the tongue is less than 10 nC due to negative phase of biphasic pulse.

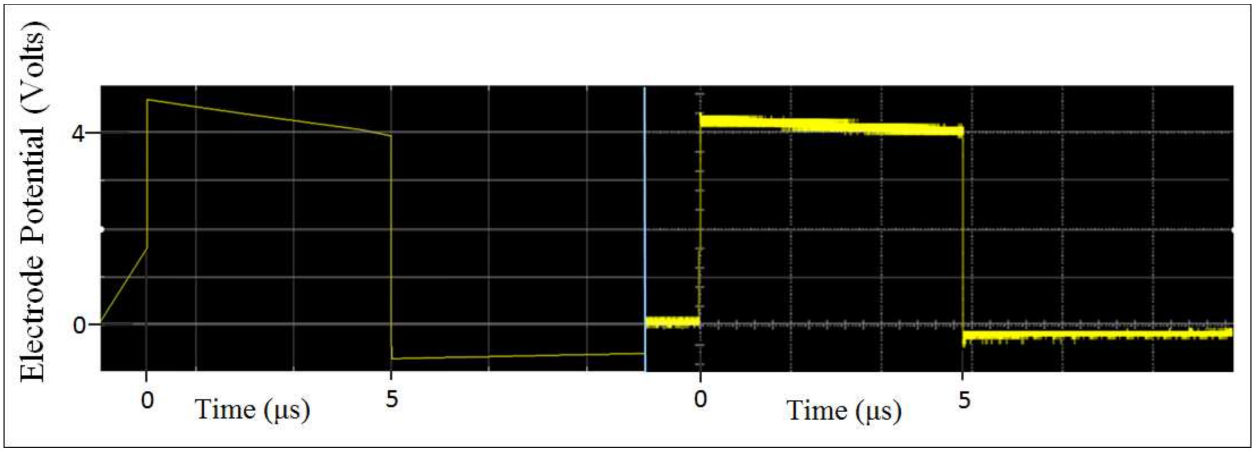


Figure 11: Left: Modeled voltage at electrode-tongue interface for an active electrode on Cthulhu. Right: Measured voltage at electrode tongue interface for an active electrode on Cthulhu.

2.4 TERRA DESIGN

The Terra/LEO series of devices are a progression of wireless tongue stimulation prototypes used for research and demonstration purposes. Terra research prototypes currently keep all batteries and circuitry outside of the mouth for convenience and participant safety, while LEO demonstration prototypes are form factor proof of concept designs that demonstrate the packaging of all components in a mouth-sized device. LEO demonstration prototypes, utilizing LED lights in place of electrodes, were also developed to provide visual input to participants during experiments to help subjects “visualize” the stimulus on their tongue. This method has not yet been implemented in studies described in this thesis. Firmware is updated on both devices wirelessly via Bluetooth.

The Terra 3 tongue stimulation device manufactured by Sapien LLC is shown in Figure 12. This device was used to generate electrical pulses on an electrode array in response to data received over Bluetooth module or USB cable. The device had the same stimulation circuit as a single, 18-channel module from the Tickler or Cthulhu stimulation devices and stimulated nerves on the surface of the tongue in a similar manner to the Cthulhu device. Electrode contact resistance, and thus current and charge transfer characteristics differed from the Cthulhu device due to electrode geometry.

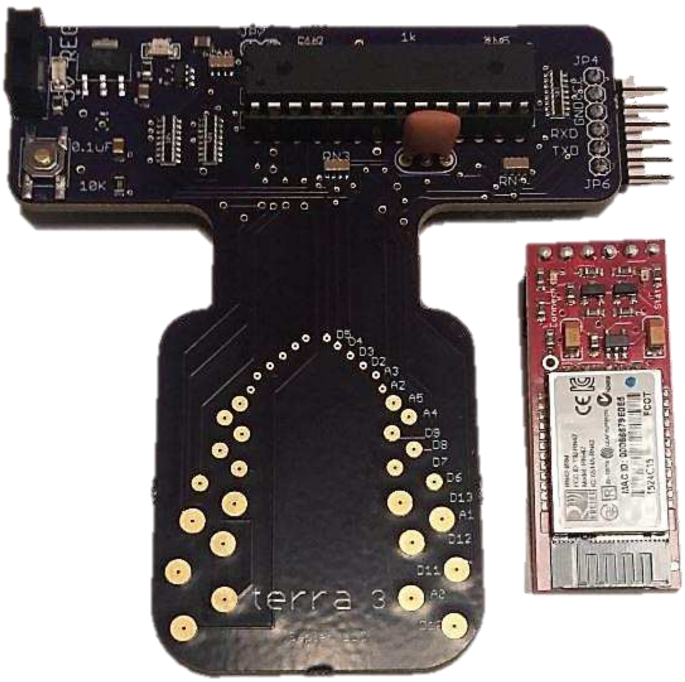


Figure 12: A Terra 3 Mouthpiece manufactured by Sapien LLC. The device electrically stimulates the tongue in response to spectral audio information received over Bluetooth. Electrode size and spacing vary according to data from experiment one on sensitivity and discrimination ability of the tongue.

The electrode array on the Terra 3 device was designed from preliminary results from tongue sensitivity and discrimination ability studies. To size and space electrodes, loci were staggered symmetrically along two identical pathways symmetric about the centerline of the tongue. The pathways were chosen to maximize the length of the pathway inside high sensitivity areas of the tongue according to average sensitivity maps of all tested participants’ tongues at the time of design. Electrode size and spacing along the pathways were determined by the sensitivity and discrimination ability of the tongue at that point along the pathway. Electrodes were made of gold plated vias placed on a circuit board with a hole diameter of 0.4mm and an outer diameter of either 1mm, 2mm, or 3mm depending on electrode location. Spacing varied from 1.5mm to 6.2mm based on electrode location. Electrodes directly opposite one another across the centerline of the array were electrically connected and stimulation on electrodes was symmetric about the centerline of the tongue.

The same microcontroller output waveforms from the Cthulhu, were used in the Terra device, though the measured output waveform of the device was slightly different due to the fact that electrode contact resistance and capacitance varied by the size of the electrode. Two and 3 mm diameter electrodes were estimated to have lower contact resistance (approximately 200Ω and 100Ω respectively) compared to electrodes used on the Cthulhu device. The lower contact resistance resulted in a shorter RC time constant for active 2 and 3mm diameter electrodes, slightly shortening the charging and discharging time of the capacitors as can be seen from modeled and measured outputs of voltage of a 3mm electrode in Figure 13. Due to the lower resistance, the modeled charge accumulation on the tongue at the electrode also decayed faster in our model as can be seen in Figure 14. The Simulink model for a 3mm active electrode on the Terra 3 device can be found in Figure 15. LEO demonstration prototypes, used uniformly sized LED's in lieu of electrodes. LED's were arranged in a line roughly following the pathways used on the terra prototypes.

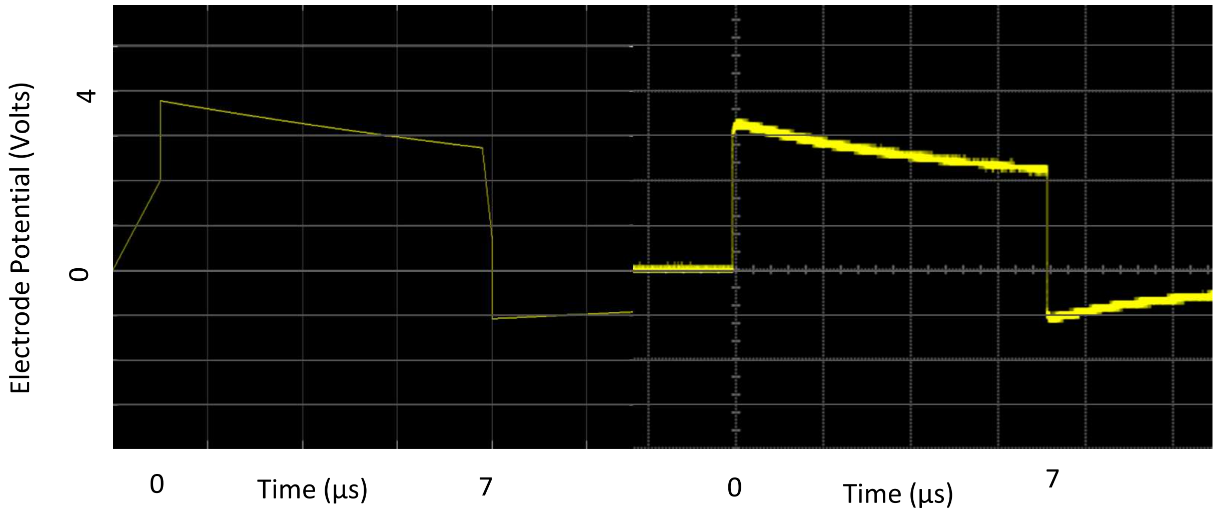


Figure 13: Left: Modeled voltage at electrode tongue interface for an active electrode on Terra 3. Right: Measured voltage at electrode-tongue interface for and active electrode on Terra 3.

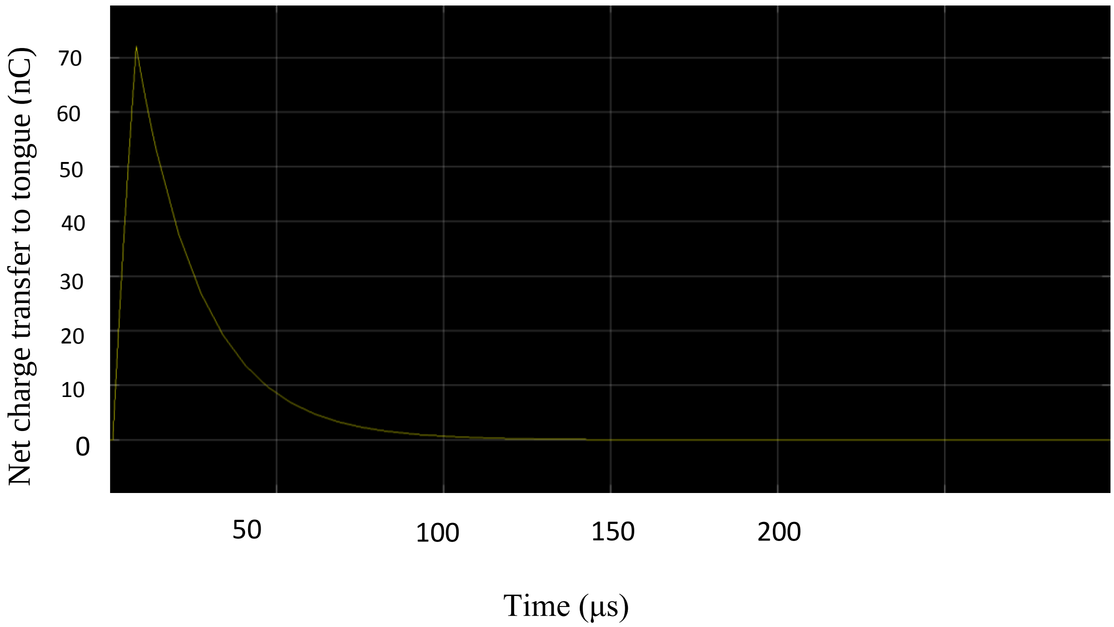


Figure 14: Coulomb charge transferred to tongue for a single pulse. Approximately 50 μs after pulse initiation, the net charge transfer to the tongue is less than 10nC due to negative phase of biphasic pulse.

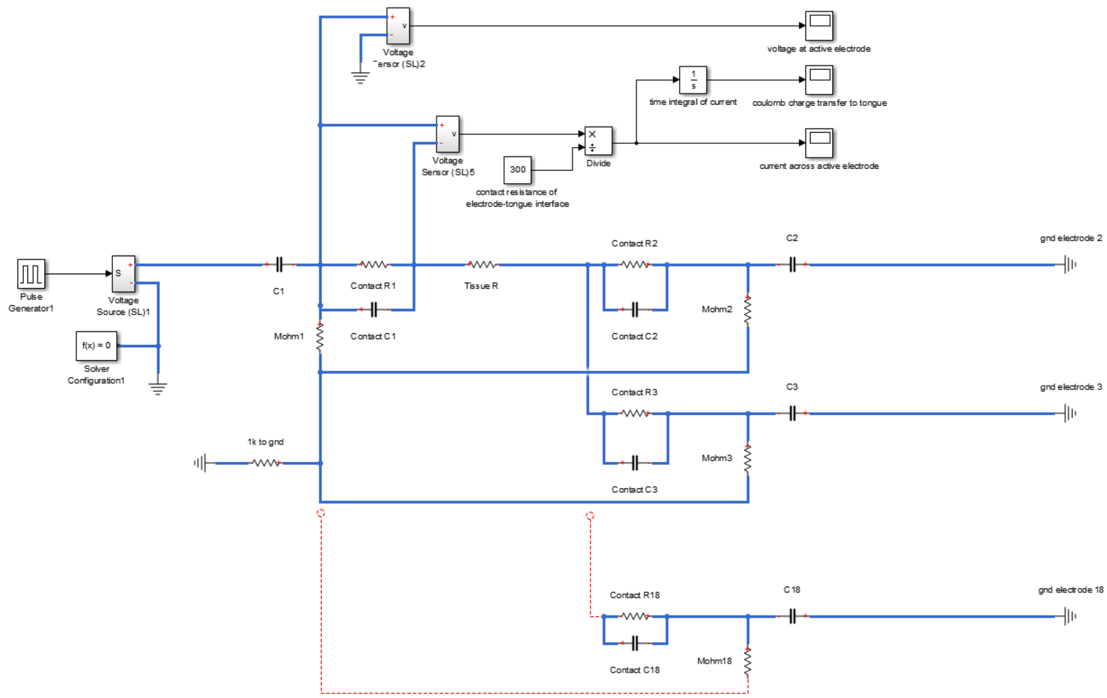


Figure 15: Equivalent Circuit for the Terra Device. Monitor devices can be seen at the top of the figure. Contact R's varied from 100Ω to 300Ω depending on the size of the electrode they modeled. Contact C's were modeled as 0.5 nF. Tissue R was considered negligible and is modeled as 0Ω.

3. EXPERIMENT ONE

Despite interest in the tongue as a location for stimulation in sensory substitution, little data is available on the tongues sensitivity to electrical stimulus and how this changes across the surface of the tongue. In efforts to achieve greater success in audio-lingual sensory substitution applications, we performed an experiment to carefully map the electrotactile responsiveness of the tongue surface.

3.1 MATERIALS AND METHODS FOR EXPERIMENT

One Cthulhu tongue stimulation device was used in this study as well as a mouthpiece assembly for each participant.

3.2 EXPERIMENTAL PROCEDURE

Fourteen healthy adult volunteers were used for the experiments. Protocols were approved by the Internal Review Board at Colorado State University and all volunteers completed informed written consent forms prior to participation. Current or past neurological or oral health problems were used as exclusion criteria. For example, subjects with mouth sores, infections, pacemakers or nerve stimulators were not included in studies. Each candidate's verbal responses to health-related questions were reviewed. The health questions were relevant to the study and data analysis as we were interested in factors that might affect oral sensitivity. Furthermore, we excluded persons who smoke or chew tobacco habitually as these activities tend to reduce the tactile sensitivity in the oral cavity.

Subjects placed the mouthpiece consisting of an electrode array and stop pad in their mouths with the stop pad indexed to the first position so that the tip of the tongue was stimulated.

Nine electrodes on the array were activated with PW and OBN set to 5. The researcher then incrementally adjusted simultaneously the PW and OBN waveform parameters of the stimulation up or down according to input from the participant who was asked to indicate when the stimulation was at a highly noticeable but comfortable level. These parameters were maintained for the duration of the experiment to ensure that all testing was conducted within a comfortable electrotactile intensity range for the individual subject. Individuals were assigned a code that identified their gender, and preferred intensity setting. No names were used. An example of a participant code could be: female, intensity level 7 - F1-7, or male, intensity level 5 - M1-5. Any records that could link participants to their test data were kept in a locked filing cabinet.

Subjects then experienced an electrotactile pattern on an area of the array and were asked to record on a checklist whether they felt one, two or zero discreet sensations and to rate the perceived intensity of the sensation(s) on a scale from 1 to 10. The investigator then proceeded to the next preset stimulation pattern and the process was repeated. Participants were instructed to spend at most one or two seconds recording responses to each stimulus due to the fact that the intensity of sensations faded quickly.

The patterns experienced by the participant were generated by random two point discrimination tests on 24 loci across the surface of the array. The two point stimuli were generated by dividing the 5x20 array into 4 5x5 sub-arrays as shown in Figure 16. Three rows and 3 columns of electrodes were selected in each sub-array as shown by the red and blue lines in Figure 17. In each row and each column, 4 pairs of electrodes that were 8, 6, 4, or 2 mm center to center apart were recorded in a list. The electrode pairs were centered in their respective row or column, but due to geometric constraints, may have been shifted off-center in their row or column by 2mm (one electrode space). These row/column pairs were randomized in a list and mixed with another list of 20 random, single electrodes. This gave 116 stimulus patterns. One list of the 116 stimulus patterns was generated and randomized for each of the 4 positions in which the array could be positioned in the mouth. Each of these 4 lists was referred to as a “script 1-4” with script 1 being the list of electrodes that were activated when the mouthpiece was placed at the first position at the tip of the tongue and script 4 being the list of electrodes that were activated when the mouthpiece was indexed to the back of the tongue. A graphic of active electrode locations for all tested 8mm two-point discrimination tests for a single sub array is shown in figure 18. The 16 total sub-arrays shown in this graphic are the result of indexing the 4 sub arrays on the mouthpiece in figure 16 to the four discreet locations in the mouth. Each of the 16 sub arrays was tested for 2, 4, 6, and 8mm discrimination ability in each of the 3 rows and 3 columns in the sub-array. This gave 464 separate patterns across a 4cm by 4cm area of each participant’s tongue (384 of these patterns were from two point discrimination tests, and the remaining 80 were single electrode stimulus at random locations).

Figure 16: The electrode array on an assembled mouthpiece shown divided into four 5x5 sub-arrays.

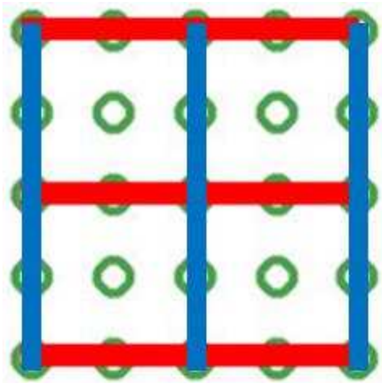


Figure 17: A 5x5 sub-arrays showing stimulation columns (blue) and rows (red) on which electrodes of varying distances were activated.

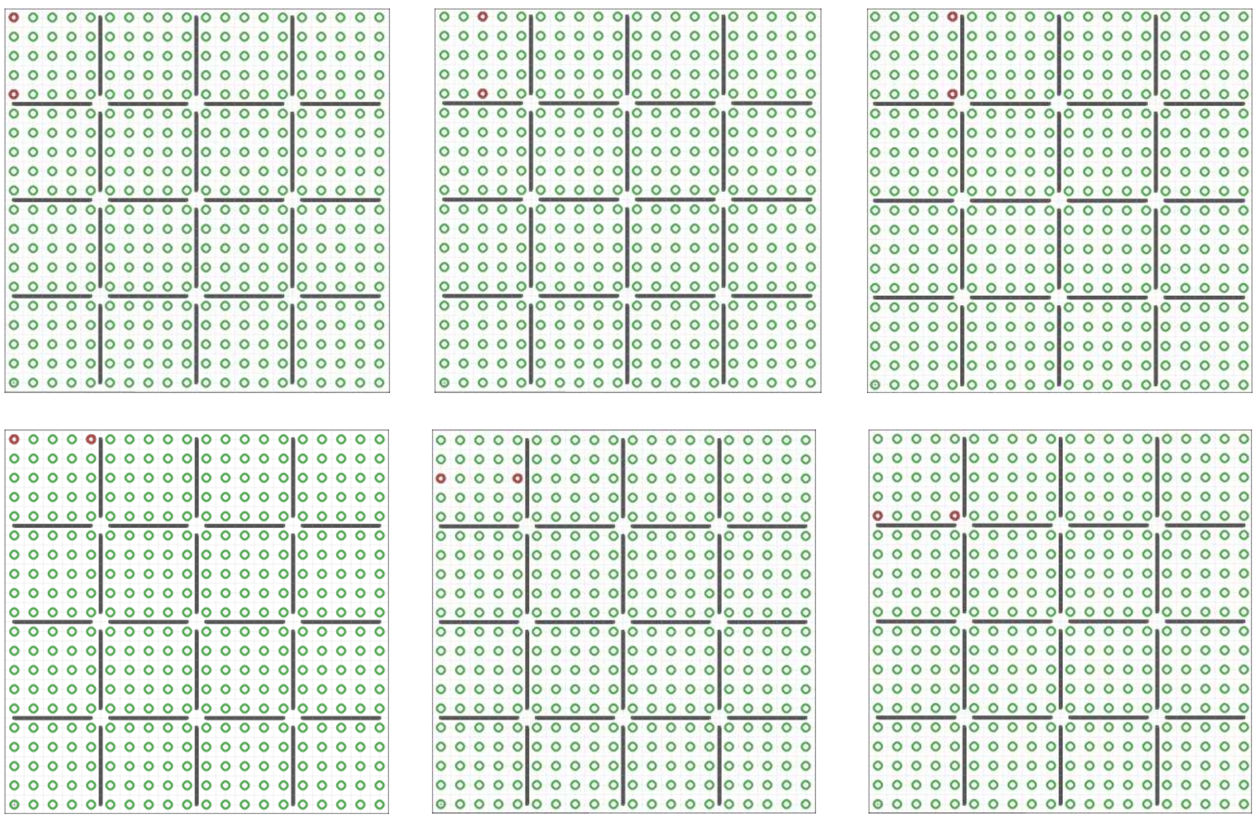


Figure 18: A graphic demonstrating a 400 electrode grid covering a 40mm by 40mm area of the tongue. This was achieved by indexing the four 5x5 sub arrays on the mouthpiece to 4 discrete locations on the tongue. Red electrodes in the top left sub-array of each grid shows all 8mm distance active electrode pairs in a single sub-array.

Participant responses were manually entered into an Excel spreadsheet that compared the perceived number of electrodes for each stimulus to the actual number of electrodes that were activated during that stimulus. The spreadsheet also found the location of each stimulus on the tongue. The perceived intensity of each stimulus was compared to the number of activated electrodes, the center to center distance of activated electrode(s), and the electrode(s) location on the tongue.

The goal of the analysis was to determine how many electrodes could be placed on an array on the tongue so that each electrode on the array produces a distinct sensation and "simultaneously" active electrodes do not perceptually interact with each other. (Simultaneously active electrodes are not actually active at the same time due to the waveform structure described above, but sensations from these electrodes are perceived to be simultaneous due to the small time parameters of the waveform). To ensure distinct sensations, the distance between adjacent electrodes must be sufficiently large so that nerve fibers stimulated by one electrode are not stimulated by adjacent electrodes.

From responses to two-point discrimination tests, the smallest tested distance for which a participant could discern two distinct sensations was determined for both horizontally and vertically oriented electrodes on 48 loci for each participant. For loci on the tongue where two distinct sensations could not be distinguished at the maximal 8mm separation, the two-point discrimination distance was assumed to be 1cm. Distances between loci varied from 2mm to 10mm and values between loci were interpolated on a grid with 2mm spacing using an iterative method implemented in Excel until values converged. This data was used to calculate the dimensions of a rectangle at each point that would contain the receptive fields activated by an electrode placed at its center. From this calculation, the total number of electrodes that could be placed on the 4cm by 4cm tested area of the tongue without influencing the perception of adjacent stimuli was calculated for each participant.

3.3 RESULTS

The maximum number of electrodes that could be placed on an array for the 14 participants was highly variable, ranging from 17 to 99 as shown in Table 1. The mean number of electrodes for all participants was 43 with a standard deviation of 26. Using values in the literature of 2-5 bps per electrode, the immediately achievable information transfer capability for an electrode array using the mean number of electrodes is between 86 and 215 bps, sufficient to communicate phonetic information to a person using existing encoding and stimulation methods.

Table 1: Maximal possible electrodes on a 4cm by 4cm array for each participant based on receptive field estimation from two point discrimination tests.

Participant	Maximum Possible Number of Electrodes
1	27
2	85
3	34
4	67
5	99
6	25
7	33
8	35
9	20
10	65
11	17
12	23
13	54
14	19

Our calculated transfer rate is at the lower end of our initial estimate using values interpolated from Maeyama and Platigg's four data points. This is due to lower measurements for discrimination ability using our stimulation method over a larger area near the posterior half of the tested area of the tongue than was predicted by our initial model using Maeyama and Platigg's data [49]. An array designed from this data for the participant with the highest electrode count could conceivably communicate up to 500 bps of audio information to a user using our stimulus. This is near the quality of proprietary audio codecs used for spoken language [43]. Electrode arrays designed for the participant with the poorest discrimination ability would still be able to communicate basic phonetic information to a user at a rate of 85 bps using our stimulus if 5 bps or greater per electrode could be achieved. Using estimated information transfer rates per stimulator calculated for experienced Braille users, the total achievable information transfer rates for an experienced lingual electrode array user could be as high as 1,425 bps.

3.4 DISCUSSION

The baud-per-stimulator estimation used in our analysis was derived from studies that used different stimulus methods than our own, and while our estimation of achievable baud rates of the human tongue provide a good starting point for further study, additional studies will be performed to more accurately estimate the achievable information throughput of the tongue using our specific stimulation methods. Tactile information encoding methods using many dimensions, such as time, space, and direction, are believed to reliably communicate more information to a person than encoding methods using less dimensions [44]. We suspect that the achievable throughput of a multi-electrode array could be greatly influenced by the encoding method used to communicate information, thus achievable baud rates for specific encoding methods should also be estimated.

We have found that the tip of the tongue is highly sensitive to our method of electrotactile stimulus when measuring perceived intensity of stimulus and two-point discrimination ability, this is consistent with studies by others on lingual sensitivity [49] [66][74][75][76]. Figure 19 and Figure 20 show that the mean two-point discrimination ability for all 14 participants is very good at the tip of the tongue for electrode pairs oriented both vertically and horizontally. The sides and posterior region of the tested area had significantly poorer discrimination ability than the tip of the tongue. The minimum two-point discrimination distance for the posterior half of the tested area of the tongues of most participants was greater than the maximum distance (8mm) our devices were set up to test. Thus there is no data over a large area of the tongue for discrimination distance. In our analysis, this area was assumed to have a minimum discrimination distance of 10mm, which is likely a very poor assumption and likely affects the accuracy of our results related to discrimination ability over the posterior two thirds of the tested region of the tongue. This has little effect on our estimates for achievable baud rate. Different electrode geometry or stimulation method could result in better discrimination ability and better sensitivity measurements over a larger area of the tongue.

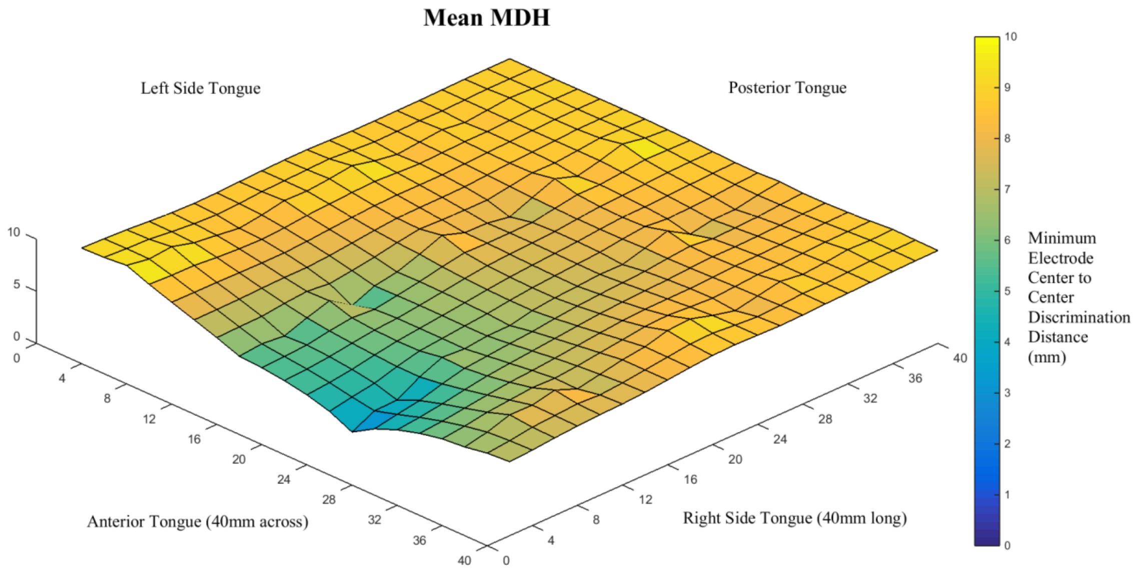


Figure 19: An average horizontal discrimination ability map for all 14 participants. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Minimum two-point discrimination ability across the surface of the tongue is represented in color with blue regions showing good discrimination ability and yellow regions showing poor discrimination ability. Discrimination ability is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, discrimination ability for two stimuli oriented perpendicular to the length of the tongue is very good near the tip of the tongue, and very poor over a larger area of the tongue including the sides and back of tongue.

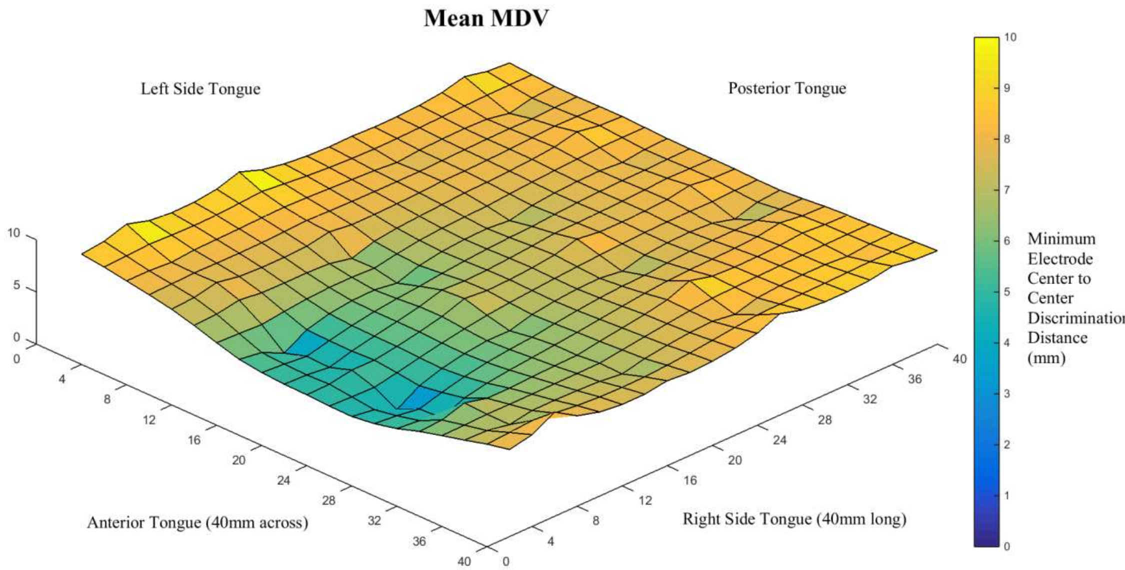


Figure 20: An average vertical discrimination ability map for all 14 participants. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Minimum two-point discrimination ability across the surface of the tongue is represented in color with blue regions showing good discrimination ability and yellow regions showing poor discrimination ability. Discrimination ability is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, discrimination ability for two stimuli oriented parallel to the length of the tongue is very good near the tip of the tongue, and very poor over a larger area of the tongue including the sides and back of tongue.

Figure 21 through Figure 28, show that the sides and posterior of the tested region of the tongue are on average significantly less sensitive than the tip by our metrics. These figures show that this trend is consistent for average reported perceived intensities for stimulus from electrode pairs separated by 2, 4, 6, and 8 mm and oriented in both the vertical and horizontal directions.

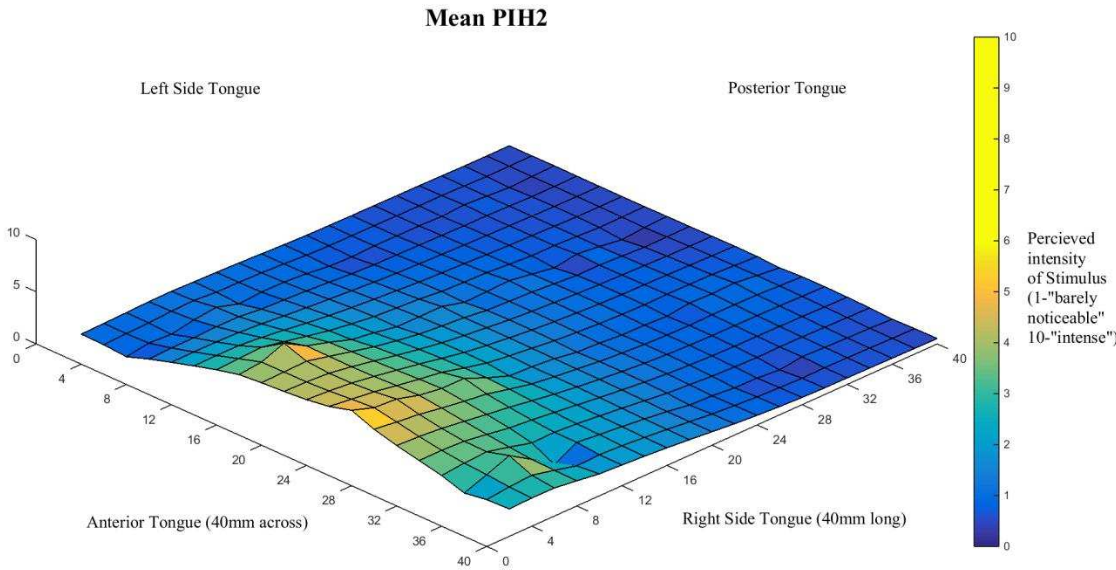


Figure 21: An average horizontal perceived intensity map for all 14 participants at 2mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented perpendicular to the length of the tongue at 2mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

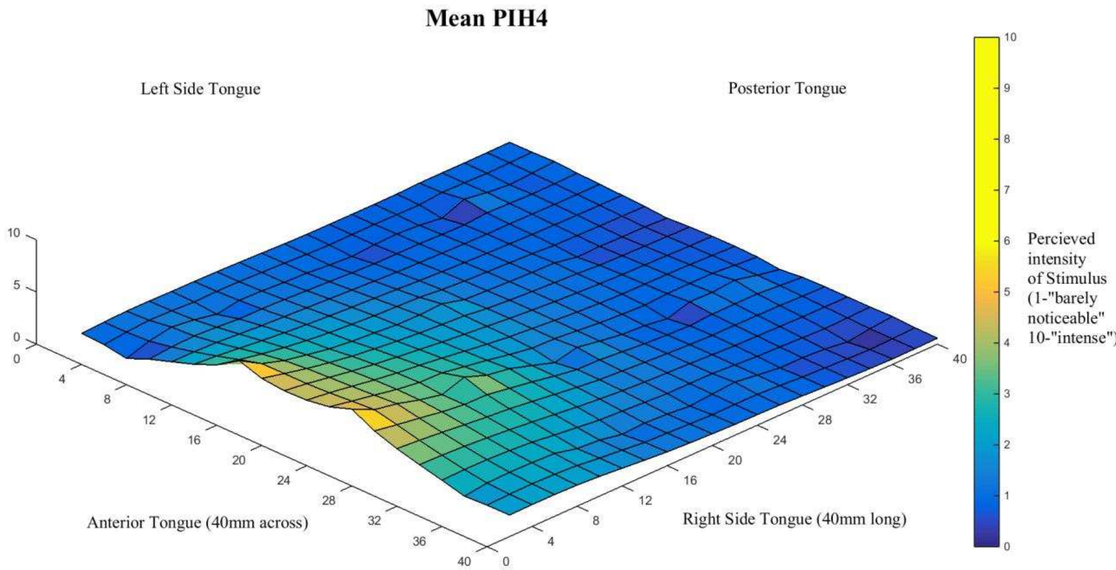


Figure 22: An average horizontal perceived intensity map for all 14 participants at 4mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented perpendicular to the length of the tongue at 4mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

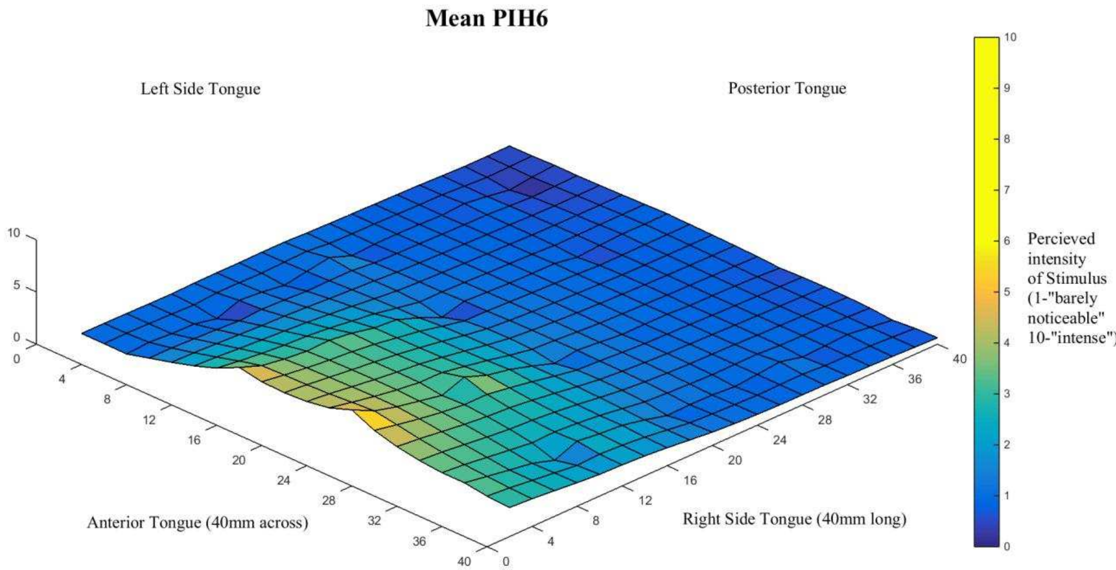


Figure 23: An average horizontal perceived intensity map for all 14 participants at 6mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented perpendicular to the length of the tongue at 6mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

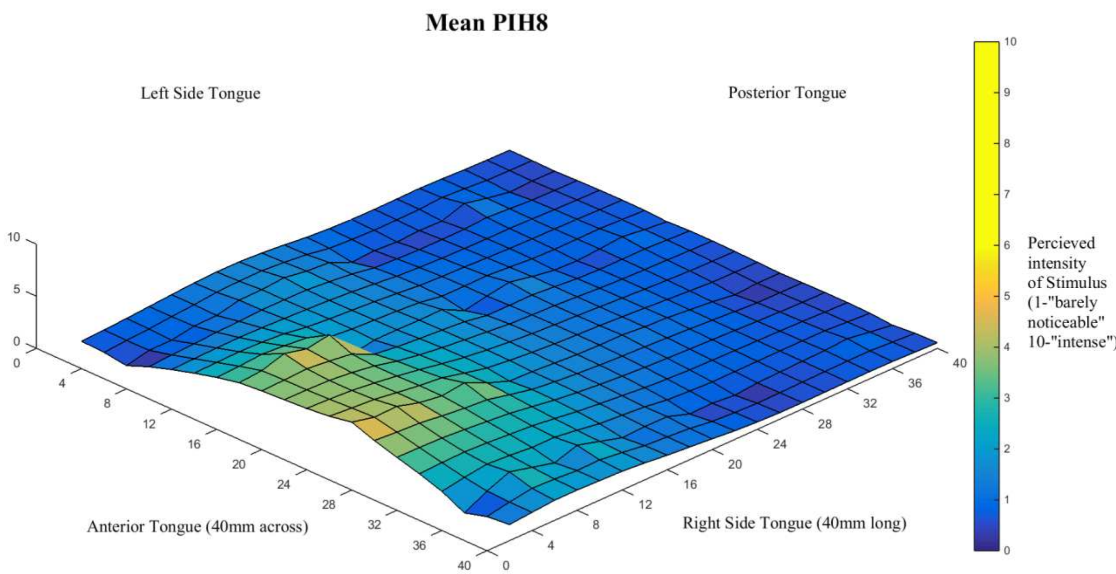


Figure 24: An average horizontal perceived intensity map for all 14 participants at 8mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented perpendicular to the length of the tongue at 8mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

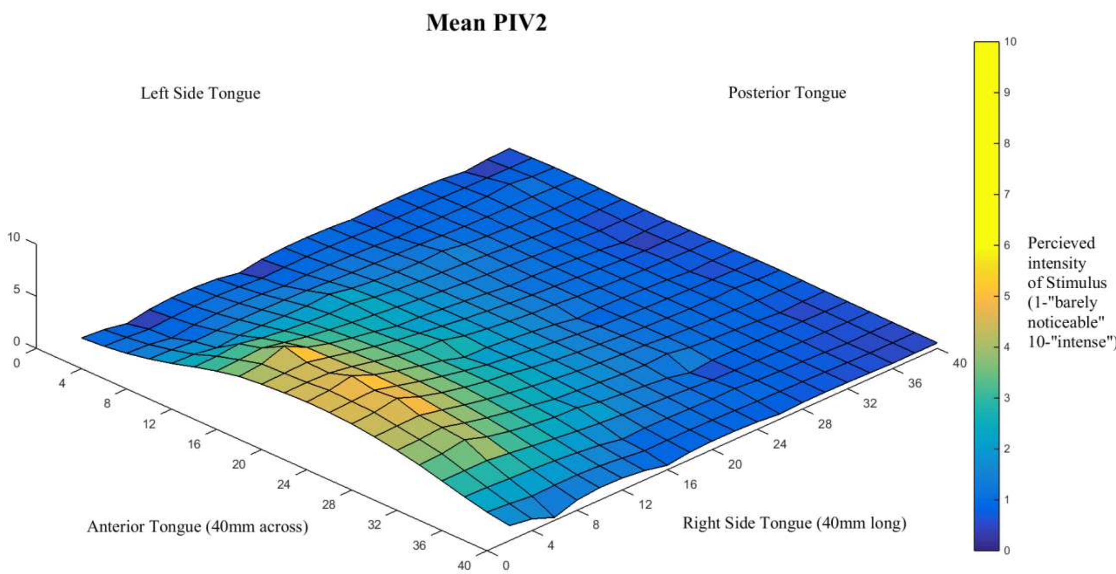


Figure 25: An average vertical perceived intensity map for all 14 participants at 2mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented parallel to the length of the tongue at 2mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

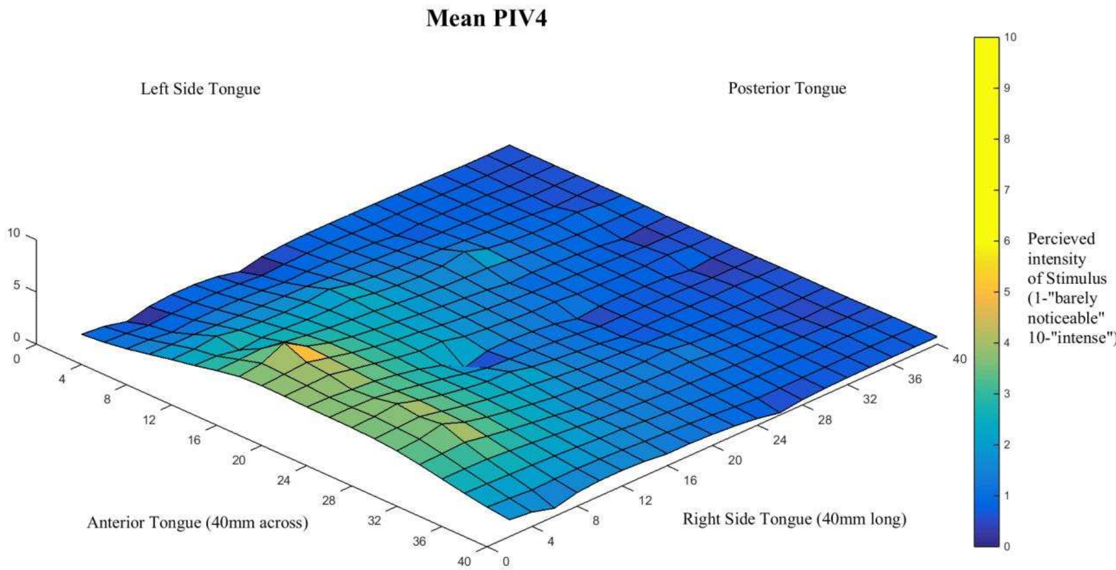


Figure 26: An average vertical perceived intensity map for all 14 participants at 4mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented parallel to the length of the tongue at 4mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

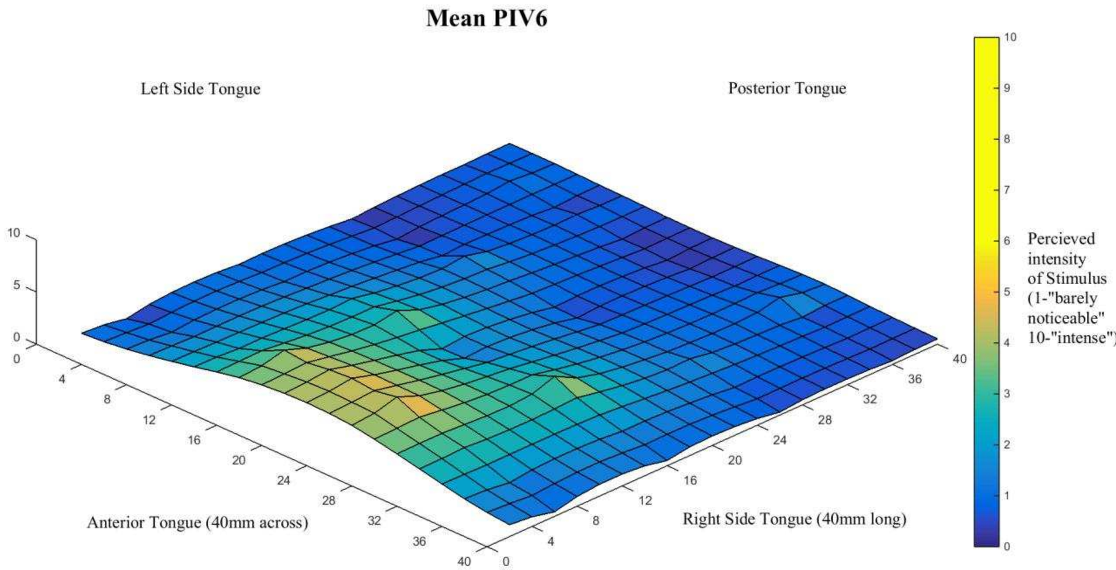


Figure 27: An average vertical perceived intensity map for all 14 participants at 6mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the “Anterior Tongue” label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the “Right Side Tongue” label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented parallel to the length of the tongue at 6mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

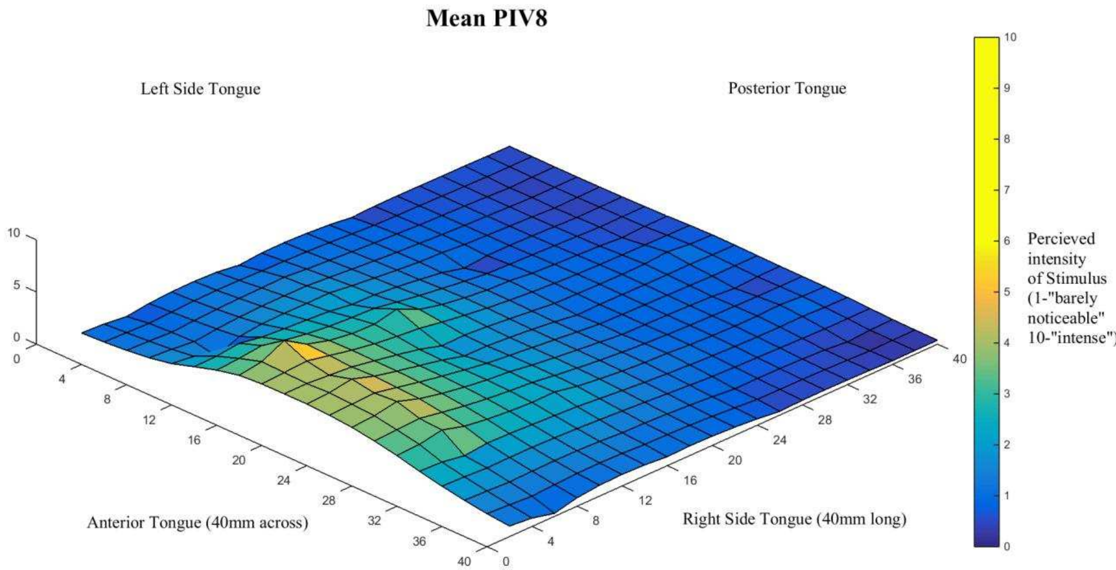


Figure 28: An average vertical perceived intensity map for all 14 participants at 8mm electrode spacing. A 40mm by 40mm tested region is shown. Edges of the tested area which are oriented on the left, right, anterior, and posterior regions of the tongue are labeled. Distance in mm from the leftmost edge of the tested region is shown along the axis located adjacent to the "Anterior Tongue" label. Distance in mm from the tip of the tongue is shown along the axis located adjacent to the "Right Side Tongue" label. Reported perceived intensity across the surface of the tongue is represented in color with yellow regions showing high perceived intensity and blue regions showing low perceived intensity. Perceived intensity is also represented in the distance of the surface from the plane created by the tongue width and tongue length axis. The figure shows that in general, perceived intensity of two stimuli oriented parallel to the length of the tongue at 8mm center to center spacing is larger near the tip of the tongue, and low over a larger area of the tongue including the sides and back of tongue.

An interesting finding that has also been observed prior to our work is that some participants have significantly better discrimination ability and higher sensitivity on one side of their tongue compared to the other side, suggesting that these participants are right and left tongue dominant, similar to the phenomenon of right and left handedness [76]. The same mechanisms which govern the phenomenon of dominant hands, eyes and feet, may also affect the tongue. Alternatively, the sided dominance observed in this study could result from environmental factors that the tongue experiences such as the shape of the individuals oral cavity. It is possible that slight asymmetry in the teeth may create a situation where the tongue is stimulated more on one side than the other during acts of chewing or talking, resulting in greater sensitivity on one side of the tongue.

While the overall sensitivity of the tongue and exact geometry of sensitive areas varied greatly from person to person, there were certain features common to most participants. Besides the tip of the tongue being the most sensitive area by both metrics, there was often higher sensitivity just off the center line of the tongue on the posterior ¾'s of the tested area of the tongue than there was directly on the centerline.

Our goal in this research was to collect and present data that will enable ourselves and others to design devices that can reliably produce noticeable and distinct sensations on the tongue. Our primary focus was to quantify the discrimination ability across the surface of the tongue, to understand how a given stimulus is perceived at different locations on the tongue, and to understand how these qualities vary from person to person. A secondary focus was to investigate whether or not there was an easy way to predict these qualities in a person. Analysis of responses from the 14 participants by a statistics consulting group led by Dr. Phil Turk and Veronica Burt confirm that lateral and vertical location of a tested locus are highly significant contributors to the participant response for both perceived intensity (p-value <0.0001) and perceived number of stimuli (p-value <0.0001). Distance between points for two-point discrimination tests was shown to have a significant effect on perceived intensity with a confidence interval of 90% (p-value 0.0562). Additional studies on more participants may show significance at 95% confidence. Analysis also confirms that distance between electrodes affects the perceived number of electrodes (p-value 0.0234). These results indicate that in future studies, testing one of either perceived intensity or perceived number may allow us to predict the other characteristic with a reasonable level of certainty.

Our methods can be used to map the sensitivity of a person’s tongue, from which a custom electrode array can be designed that can produce quality electrotactile sensations for the individual. Because of similarities in the geometry of sensitive regions of participants tongues, we believe it is possible to design a spectrum of electrode arrays from a single prototype that would allow for stimulation of the tongue of comparable quality to an array custom built for an individual. Surface area of electrodes would be changed from the prototype to reflect differences in sensitivity because the number of nerve endings stimulated has been shown to correlate to the perceived intensity of a stimulus [75][77]. Varied spacing of electrodes in arrays is necessary to reflect the varying discrimination abilities. Currently, there is not a simple test to determine the sensitivity or discrimination ability of an individual’s tongue. Our current test takes approximately one hour to complete. Visual tests, such as counting papillae (small bump-like structures on the surface of the tongue containing tastebuds) from a photograph of an individual’s tongue, may be a better way to estimate sensitivity in the future if papillae density is found to correlate to electrotactile sensitivity.

3.5 FUTURE AND ONGOING WORK

We are currently analyzing data from additional experiments conducted in a similar manner. In these unfinished studies, we tested over 10 additional participants multiple times over a period of weeks. Though still ongoing, it has been found that participant responses did not differ significantly in each of the tests that were taken days or weeks apart, although most participants trended towards slightly better discrimination ability on their second and third studies.

Prior to these ongoing studies, each participants tongue was also dyed with blue food dye and photographed. From these photographs, researchers counted the number of fungiform papillae in different regions of the tongue, and measured each papillae diameter. It is thus far not clear whether papillae density is a good indication of discrimination ability, or sensitivity as measured by perceived intensity of a given stimulus.

Additional studies on the discrimination ability of participant's tongues will be performed with equipment that is set up to activate electrodes that are greater than 8mm apart. This would provide more information on discrimination distances over a greater area of the tongue and may show a stronger relationship between perceived intensity and discrimination distances.

It was assumed that setting the intensity of stimulus at the beginning of the study to a "highly noticeable but not uncomfortable" level for each individual would normalize data sufficiently for comparisons. However, some participants reported consistently higher values for perceived intensity than others. For better comparisons, additional analysis should be done using data from the study that has been somehow normalized (perhaps using a global mean or mode) so that the difference between participants normalized whole tongue intensity averages are smaller.

Additional studies on the effects that electrode size and geometry, and stimulus waveform have on perception would help provide a better and more complete understanding of electrotactile stimulus of lingual tissue.

4. EXPERIMENT TWO

In experiment one, it was found that lingual sensitivity and discrimination ability varied greatly between our participants, though for all participants, the tip of the tongue was highly sensitive and the rest of the tongue had relatively poor discrimination ability. Results suggested that even participants with the lowest sensitivity and discrimination ability could still receive phonetic information on their tongues at rates fast enough for normal conversation. Experiment two served to test this directly.

4.1 INTRODUCTION

Electrotactile stimulation of the tongue has proven successful at communicating high baudrate information to a person in vision and balance studies[78][25]. Limited studies on audio-lingual sensory substitution have also realized some success,[79][40][39] though it was suggested that these studies were not sufficiently long to allow participants to train long enough before being tested. Tactile stimulus on other locations has been used successfully to communicate language to a person [29]. We believe that phonetic information can be communicated to a person via the tongue using methods of stimulus described in the previous study, and a simple spectral encoding method. Furthermore we hypothesize that stimulating the tongue in a tonotopic manner will facilitate learning tactile vocabulary more readily than other artificially patterned encoding scheme.

4.2 MATERIALS AND METHODS

One Terra 3 tongue stimulation mouthpiece and one computer game were used to test how well spectral stimulation of the tongue improves over extended training sessions.

Experimental devices were developed by the author, the computer game was developed by fellow graduate student Marco Martinez with input from the author, Dr. Leslie Stone-Roy, and Josiah Rachinni.

Twelve audio clips were generated by recording a speaker reciting single and multi-syllable words. The words used in this study were chosen from young children's books and were picked to represents a variety of phonetic sounds. The words are bright, mushroom, peaches, goose, never, swim, dark, guide, shell, cooks, things, and water. Each audio clip was encoded into a tactile stimulation using either a formant-to-tactile stimulus encoding method, or a whole-phoneme-to-tactile stimulus encoding method. Each participant in the study only experienced stimuli generated from one encoding method while playing the game for the duration of the study.

In the formant encoding method, audio clips were spectrally analyzed from 200 to 5000 Hz. The base frequency for the first three formants of each audio clip at 50ms intervals was exported to a text file using the formant recognition functionality of PRAAT phonetic analysis software. During the study, software would read this file and bin the base frequency information into 18 linearly spaced bins. The first bin contained frequencies between 200 and 466 Hz, the second bin contained frequencies between 467 and 733 Hz, and so on in 266 Hz intervals. The software would then transmit bin numbers corresponding to the base frequency of the formants to the Terra 3 mouthpiece via Bluetooth every 50ms. This transmission was synchronized with playing the audio clips when in practice mode. The Terra 3 mouthpiece would then activate up to 3 electrodes on the array corresponding to the bin number and the location of the base frequency of a formant on the frequency spectrum. Figures 29 and Figure 30 demonstrate the stimulation method and show active electrodes on the array at different times for the audio clip of the word "Bright".

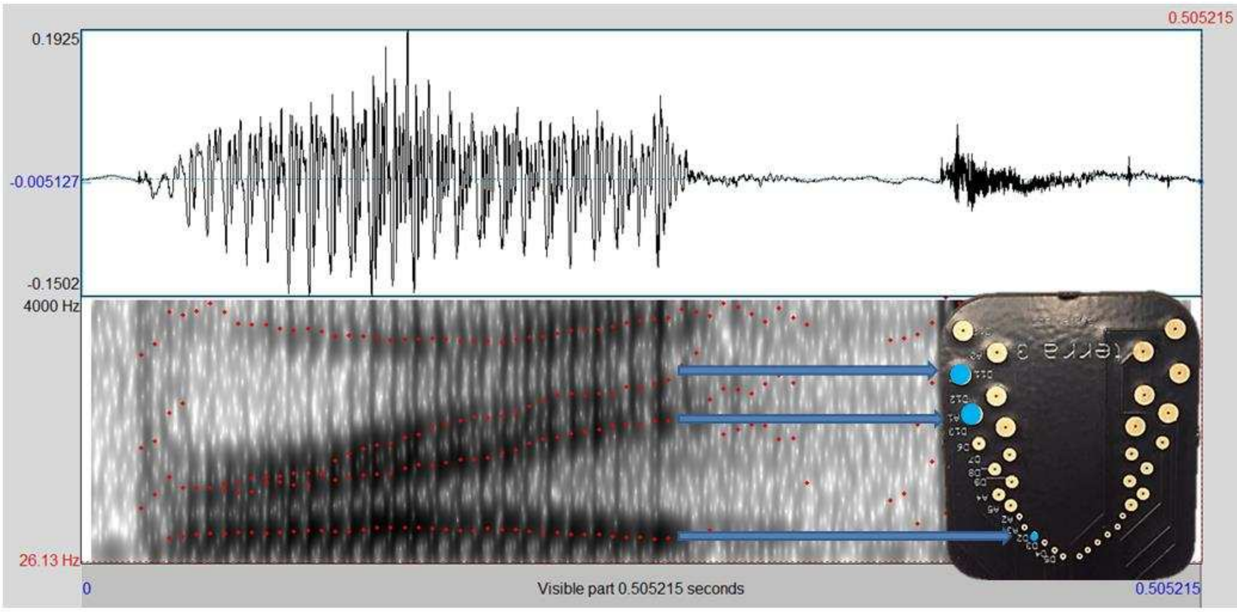


Figure 29: Spectrogram of the audio clip "Bright". Red dots show formants identified by PRAAT software. Blue dots on electrode array show active electrodes corresponding to location of formants at moment in time.

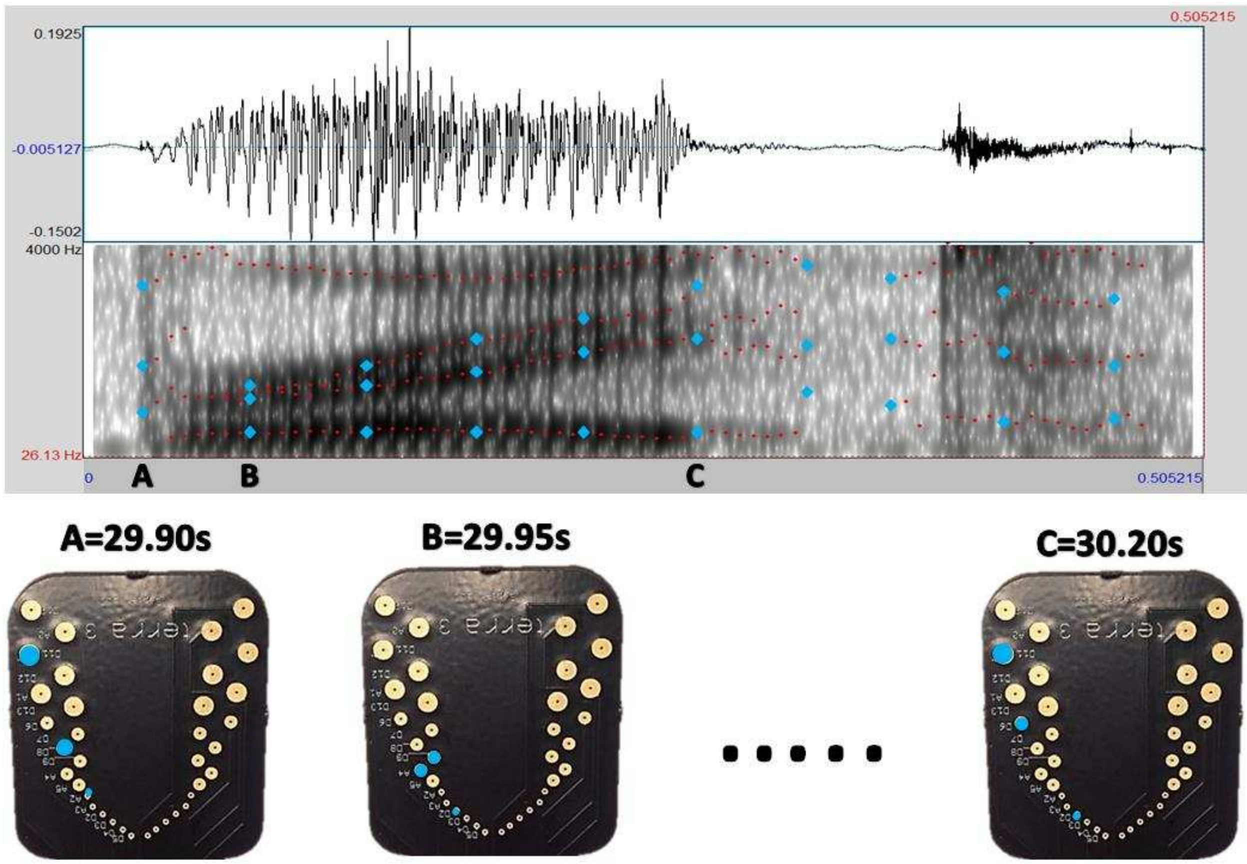


Figure 30: Spectrogram of the word "Bright" with corresponding location of active electrodes as blue dots shown in 50ms intervals and the active electrodes on the array at three points in time, A, B, and C.

For the binary encoding method, an arbitrary six bit binary value was assigned to each phoneme in the English language. Every third electrode on the Terra 3 mouthpiece represented one of six bits. These electrodes were activated during stimulation so that for the duration of each phoneme in an audio clip, the activation of the six electrodes on the array represented the bits of the six bit binary number assigned to each phoneme in the English language. An example of how the phoneme "B" in the word 'bright' is shown in Figure 31.

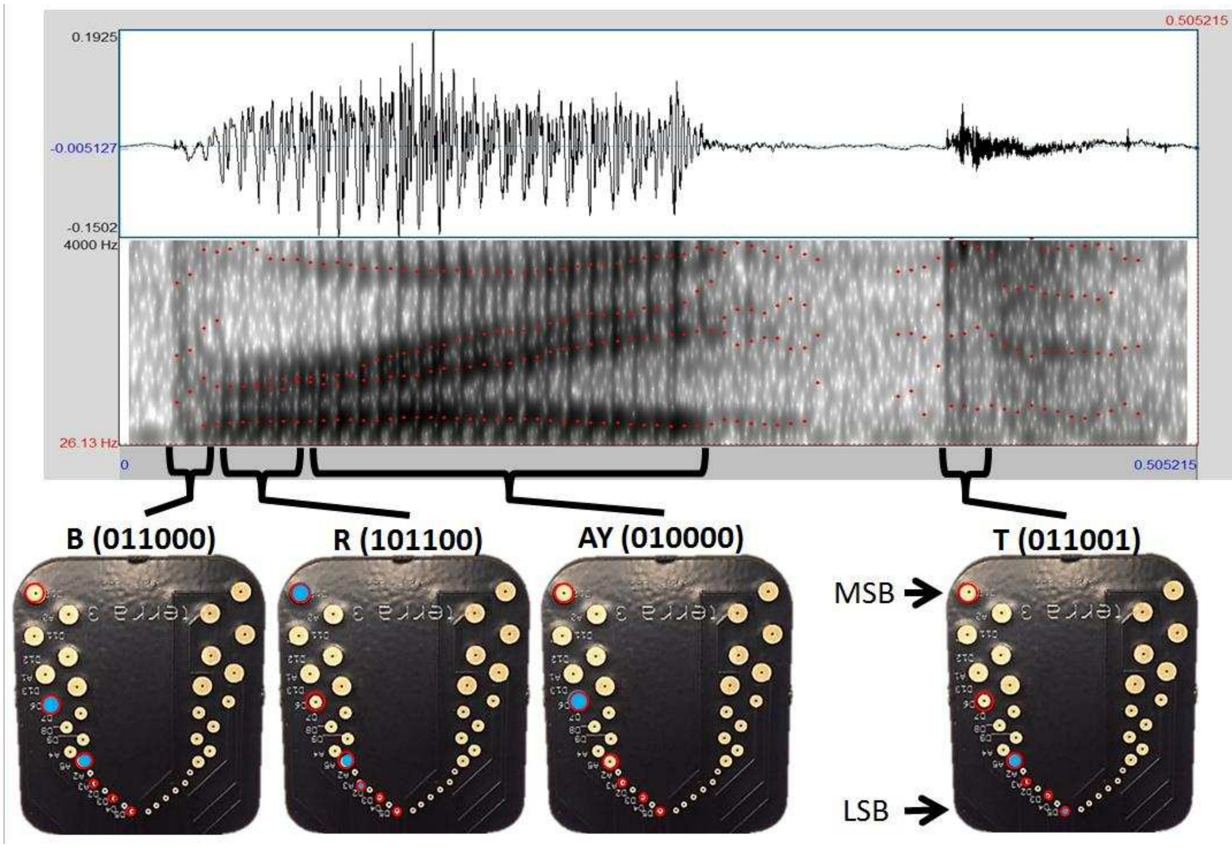


Figure 31: A spectrogram of the word "Bright" and active electrodes in blue corresponding to a binary representation of the arbitrarily assigned phoneme number. Red ringed electrodes on the Terra 3 mouthpiece show the location of the six electrodes which represent the binary number. Blue electrodes with red rings indicate electrodes which are active for the duration of the phoneme and represent values of "1" in the binary number.

In this encoding method, audio clips were spectrally analyzed in PRAAT software and were manually transcribed into the phonetic alphabet by an undergraduate linguistics student with phonetic transcription training. The approximate start and end time of each phoneme in the audio clip relative to the beginning of the recording was also estimated. The arbitrary 6 bit binary value and corresponding decimal value assigned to each of the 46 phonemes in the English phonetic alphabet can be seen in table 2.

Table 2: Showing the 46 phonemes in the English language, with an arbitrary binary and decimal numeric value associated with each.

Phoneme	Example	Decimal Designation	Binary Value
IY	Heel	1	000001
IH	Hit	2	000010
EY	Bait	3	000011
EH	Met	4	000100
AE	Hat	5	000101
AA	Pot	6	000110
AX	Fern	7	000111
UX	Up	8	001000
UW	Soon	9	001001
UH	Foot	10	001010
OW	Boat	11	001011
AO	Fork	12	001100
OH	Hot	13	001101
AH	Bath	14	001110
EI	Wait	15	001111
AY	Kite	16	010000
OY	Coin	17	010001
OU	Bone	18	010010
AW	Cow	19	010011

IA	Ear	20	010100
EA	Air	21	010101
UA	Tour	22	010110
P	Spin	23	010111
B	Boo	24	011000
T	Stop	25	011001
D	Dog	26	011010
K	Scan	27	011011
G	Gate	28	011100
M	Mat	29	011101
N	Not	30	011110
NG	King	31	011111
F	Fat	32	100000
V	Vat	33	100001
TH	Thumb	34	100010
DH	That	35	100011
S	Sat	36	100100
Z	Zip	37	100101
SH	Mesh	38	100110
ZH	Measure	39	100111
H	Hot	40	101000
CH	Chair	41	101001
JH	Edge	42	101010

L	Lot	43	101011
R	Rot	44	101100
Y	Yawn	45	101101
W	Win	46	101110

When playing the game, when a stimulus generated for a certain word was to be felt on the tongue, software would read a text file containing the decimal designation given to each phoneme in the word, and the approximate beginning and end time of each phoneme in the word. The software would then transform the number into a binary value, and send the electrode numbers to the Terra 3 mouthpiece that corresponded to values of “1” in the binary number representing the phoneme.

One simple, text interface computer game, called the ‘vocab game’ by researchers, was used in this study. The game consists of multiple levels of gameplay, wherein a user has the option to practice tactile vocabulary words, test themselves using a flashcard function, or attempt to test out of their current level. In each level, a participant has a list of words that they try to master by being able to correctly identify the tactile stimulation generated by any word in their vocabulary list. The user can move freely between practice, flashcard, and quiz modes for any given level. In Practice mode, a user can select a word from their list, and feel the stimulation produced from the word while simultaneously listening to the audio clip of the word on a headset. In flashcard mode, the users tongue is stimulated using stimulus generated from one of the words in their list and audio clip is not played. The user then must decide what word was stimulated from a list of possible words. The user is immediately informed whether or not they guessed correctly and are prompted to move onto the next word. Quiz mode is very similar to flashcard mode, except that correct/incorrect feedback is not provided until the end of the quiz. The number of questions in the quiz for level 1 is 10. The number of questions in the quiz in each subsequent level is increased by 10. The number of vocabulary words in level 1 is three. In each subsequent level, an additional three vocabulary words are added to the existing list. To move on to the next level, the participant must attain a score of 80% correct responses in the quiz.

4.3 EXPERIMENTAL PROCEDURE

After completing at least one session from experiment 1, participants were assigned a sterilized Terra 3 mouthpiece. Participants were given a random numeric designation which they used to login to the game. After logging into the game participants put on a pair of headphones and placed the Terra 3 mouthpiece in their mouths. Participants were then free to play the game as long as they desired, though it was suggested that they play for at least 30 minutes in each session. During gameplay, participants were free to practice and test at their own pace and move freely between game modes. Participants were free to play the game at their convenience whenever an investigator was in the room.

For each participant, the software in the game recorded the amount of time the participant spent in each game mode in each level, the number of times the tactile stimulus for each word was felt, the individual responses to each stimulus during the quiz and the corresponding actual stimulus, as well as the quiz total score.

4.4 RESULTS

The game is still in a beta test stage and very little data has been collected up to the time this manuscript was written. Complete data sets are available on only two participants who have made it past the first level, partial data is available on an additional seven participants. One participant, designated M1-7, was assigned the whole phoneme binary encoding method. This participant had extensive experience with tactile stimulation and had spent multiple hours testing the formant encoding scheme of the game, for this reason, the participant was assigned the completely different phoneme binary encoding scheme. The other participant, F6-9 was assigned the formant encoding scheme, and had no previous experience with the game or encoding schemes.

The participant using the binary encoding scheme who had previous extensive experience with formant generated stimulus took a total of 5 minutes to pass level 1. The participant with no previous experience who was assigned the formant type stimulus with the game took a total of 79 minutes to pass level 1. Both Participants spent the majority of their time in flashcard mode.

Quiz scores and individual answers for level 1 were available for all nine participants. For those who used the formant encoding scheme. The two words that were most frequently confused with each other were “mushroom” and “bright”. While these two words sound very different from one another there are some similar features in the first half second of the spectral domain that may explain the confusion.

4.5 DISCUSSION

While data from this beta study is encouraging, our data pool is too small for any in-depth analysis. Feedback from participants on gameplay and difficulty has been the most valuable information gleaned from this pilot study. Participants in general completed the first level in about an hour, but had difficulty in the second level due to the significant increase in vocabulary. In future studies, words will be added incrementally, one at a time to the list of vocabulary words. Furthermore, the game will be made more fun, with sounds, pictures, and animations as rewards or encouragement.

The study needs to be adapted to allow people who are deaf or hard of hearing to participate. Visual stimuli should be included to help both people with normal hearing and those who are deaf or hard of hearing associate sounds with stimulus. LEO demonstration prototypes may be utilized for this in future studies.

A method that can be developed that allows a user to experience their own voice should be developed. Future studies will be developed that allow users to act and feel the action, and to act and interact with their prosthetic. This is a challenge with current prototypes, but may be accomplished in the future.

This study simply tested if two types of encoding methods could stimulate the tongue and allow it to be perceived at the lower end of the estimated throughput of the tongue. Simpler, more basic studies will be devised to test the time resolution and perceivability of single and multi-electrode stimulus on the tongue. A study will then be performed testing the expandability of results achieved with single and small numbers of electrodes. A simple “same or different” study using multiple numbers of electrodes, and varying stimulus time lengths could be a more direct test of baud rate capability. Word count per level also needs to be recorded to understand how many times a word must be played to recognize it from a list of words.

The current arrays are held in the mouth by holding them in with the teeth, or the hand. Variability in the position of the mouthpiece during the study seems to be a problem, future studies will use a positively placed mouthpiece.

Without additional data, few outcomes can be drawn from the study to date. Preliminary results are promising and show that for multiple participants, tactile stimulus generated from formant and whole phoneme encoding methods for 3 words can be differentiated with over 80 percent accuracy in approximately one hour of training. We also know that certain changes need to be made to the game to make it more engaging and to make the attainment of subsequent levels easier. Words need to be added incrementally one at a time instead of in groups of words. The game needs to be more interactive and allow the user to control stimulus using their own voice or some other type of intuitive, real time input, such as a slider, knob, or other mechanisms. Live voice interaction or discussion needs to be considered in future studies.

4.6 FUTURE WORK

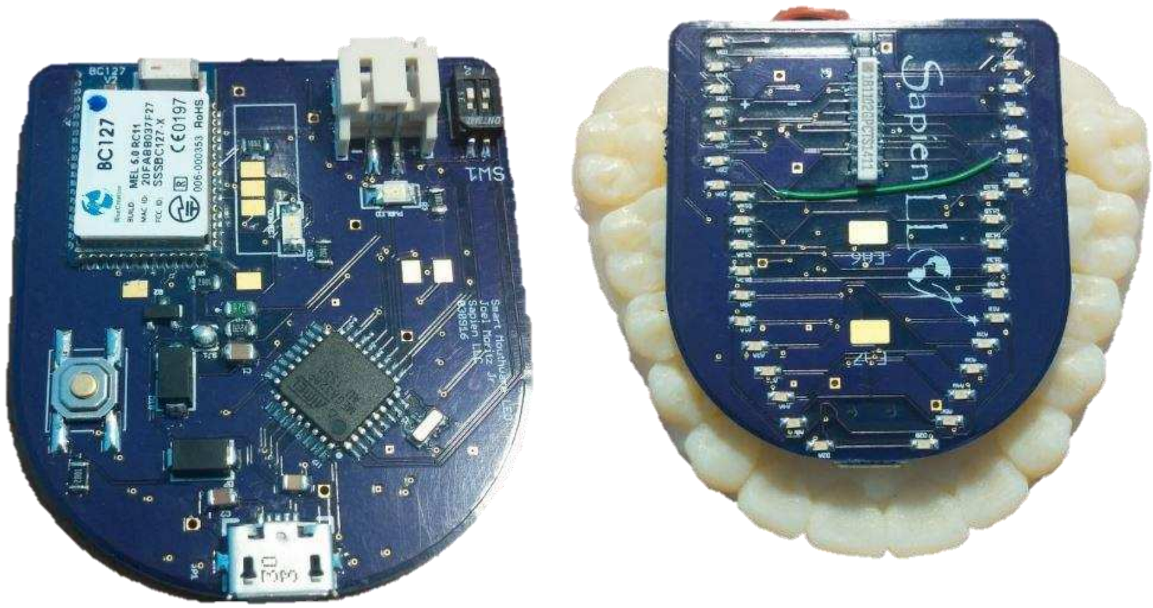
Improvements are being made to the current vocabulary game format to make the game more engaging and less difficult. A spectrum of additional studies would serve to answer some questions raised by the previous study and current beta study. Specifically, a study to test time constraints of tongue stimulus, and expandability of single electrode baud rates needs to be developed.

Currently work is underway to adapt the study to facilitate individuals who are deaf or hard of hearing. Live-voice prototypes developed by the author and Marco Martinez have also been developed and are currently being used in live-voice narrative tracking studies to evaluate their effectiveness at supplementing lip-reading for participants who are deaf or hard of hearing.

5. CONCLUSION

This project was intended to develop apparatus and methods of sending audio information to the brain using the lingual nerve, and to evaluate the technical challenges and potential solutions of designing a product using this technology. Small wireless prototypes were developed, and short unpublished studies using these devices encouraged the development of more devices and more extensive validation. More advanced and robust devices were designed and human study protocols were written. It was determined that the size of electrodes on the tongue had a great effect on the reliability of producing a sensation. Data from literature on the sensitivity of the tongue to electrotactile stimulus was limited, so additional research tools and human study protocols were developed to map the sensitivity of the tongue to our stimulus and to understand the variability of this sensitivity among participants. Results from these studies indicated that phonetic information could be communicated to a user using existing electrical tongue stimulation techniques. From preliminary data on this study, new research tools were designed that varied the size and spacing of electrodes according to available data. Software was developed to allow users to train their tongues to recognize stimulation produced by audio stimulation and record data on learning rates.

The work accomplished to date suggests that phonetic and acoustic information can be received on the tongue and processed in the brain such that with training, users can use the devices to participate in normal conversation. Literature and results from our studies suggest that the tongue is capable of receiving and transmitting information at much greater rates than what was tested in this study and that technology innovations could help realize this ability. When combined with lip reading or aided hearing, we believe that our technology could be used in future prosthesis to improve word identification and narrative tracking by at least the 20-50% observed in similar tactile hearing studies, though greater gains would be expected with additional training. We conclude that using our existing technology and methods, the tongue is capable of receiving and transmitting phonetic information at rates which enable normal conversation. Technology we have developed to date, shown in Figure 32, demonstrates that the electronics necessary to realize this data transfer can be easily embedded into small dental retainer sized devices that can in the future, be worn discreetly and comfortably in the mouth.



Figures 32: A Sapien LLC LEO demonstration mouthpiece. Left shows top of fully assembled device. Right shows the device placed in a mold of a dental patients' mouth.

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