TactTongue: Prototyping ElectroTactile Stimulations on the Tongue

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Figure 1: TactTongue is an oral interface that renders electrotactile stimulations on the tongue. (a) It consists of an electrode array that can be placed on the tongue. (b) It connects to the Arduino Uno/Nano shield and comes in a compact form factor. (c) A design tool for prototyping diverse sensations and a few tastes on the tongue. (d) TactTongue can be deployed in diverse applications such as rendering the sensation of liquid flow when a VR character drinks water or lemonade.

ABSTRACT

The tongue is a remarkable human organ with a high concentration of taste receptors and an exceptional ability to sense touch. This work uses electro-tactile stimulation to explore the intricate interplay between tactile perception and taste rendering on the tongue. To facilitate this exploration, we utilized a flexible, high-resolution electro-tactile prototyping platform that can be administered in the mouth. We have created a design tool that abstracts users from the low-level stimulation parameters, enabling them to focus on higher-level design objectives. Through this platform, we present the results of three studies. Our first study evaluates the design tool's qualitative and formative aspects. In contrast, the second study measures the qualitative attributes of the sensations produced by our device, including tactile sensations and taste. In the third study, we demonstrate the ability of our device to sense touch input through the tongue when placed on the hard palate region in the mouth. Finally, we present a range of application demonstrators that span diverse domains, including accessibility, medical surgeries, and extended reality. These demonstrators showcase the versatility and potential of our platform, highlighting its ability to enable researchers and practitioners to explore new ways of leveraging the tongue's unique capabilities. Overall, this work presents new opportunities to deploy tongue interfaces and has broad implications for designing interfaces that incorporate the tongue as a sensory organ.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**; **HCI theory, concepts and models**; **Empirical studies in HCI**.

KEYWORDS

On-Body Interaction, Epidermal Interfaces, Wearables, Haptics, Vibrotactile Actuation, Fingernail devices

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1 INTRODUCTION

The human tongue is a fascinating organ. It is in a protected environment [5, 6], is densely innervated, and has good electrical conductivity due to the presence of saliva and its tissue properties, resulting in small receptive fields that enable the detection and discrimination of closely spaced mechanical or electrotactile stimuli [86]. The human tongue consists of mechanoreceptors that help us understand food textures [8] and taste receptors that perceive diverse taste sensations. Furthermore, it has a high bandwidth to

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send information to the brain, comparable to the bandwidth offered by auditory nerve [46]. These highly desirable characteristics make the tongue an attractive medium for designing novel interactions that can be deployed in diverse application domains, including sensory substitution for accessibility and rehabilitation, augmented food perception, and eXtended Reality.

Tongue interfaces are actively being explored in the HCI research community. These include electrotactile interfaces for rendering taste [62], augmenting taste perception [63] and taste displays for reproducing taste [44] using aqueous chemical gels. The majority of work has focused on rendering and measuring the perception of taste. However, the tongue is a sense organ with a rich concentration of taste receptors and tactile mechanoreceptors [86], making it a suitable location for providing highly articulated and targeted tactile feedback. This property of the tongue has been leveraged extensively in the biomedical and neuroscience communities where the tongue has been used for sensory substitution [6] and also for providing additional tactile feedback while performing surgical operations [68]. However, such research explorations studying the close interplay between tactile feedback and taste rendering have been very minimal. Ranasinghe et al. [62] made initial explorations, but this was limited to a single electrode which was large in size, and the studies were focused on understanding the electrotactile thresholds for rendering taste.

One of the key limitations of tactile interfaces for the tongue that have been studied in HCI literature is that they are often low-resolution (mostly consisting of a single electrode) [62] and require expertise in electrical engineering and haptics to design systems that produce suitable tactile feedback on the tongue. It should also be noted that the absolute detection thresholds for electrotactile feedback on the tongue are significantly lower compared to other locations (e.g., fingertip, forearm). Hence existing electrotactile stimulation kits do not translate directly to the tongue. There is a large body of research that contributed to haptic design toolkits. These have predominantly been designed for rendering vibrotactile effects [57, 70, 76, 81, 95, 96] and do not translate for stimulation on the tongue.

Research communities in neuroscience, biomedical engineering, and surgery have contributed dense electrotactile stimulation devices [2, 31], with some of them being commercialized[1]. However, the primary focus of these works has been on the application domain. As a result, these have been designed for expert domain users, require extensive training, and are highly expensive, prohibiting their adoption as prototyping toolkits for a larger audience that includes creative designers, practitioners, and researchers.

This work makes the following contributions:

- We introduce a prototyping platform for rendering electrotactile stimulation on the tongue. It features an 18-electrode array that enables the precise rendering of spatiotemporal tactile effects on the tongue. In addition to tactile output, TactTongue can enable touch input on the tongue. Users can perform touch input by placing the device on the hard palate region of the mouth. This can be highly useful in scenarios where hands are busy/unavailable for interaction (e.g., for motor-impaired users).
- The hardware (shields for the Arduino platform) and software ecosystem enable designers to rapidly prototype diverse tactile effects on the tongue. Compared to the previously reported designs, our hardware design incorporates nearly 50% fewer components (Figure 1 b). We believe that a simpler design will significantly improve wider adoption since TactTongue can be easily replicated and reproduced without the need for expert skills in electronics. We present the first design tool that allows designers to rapidly prototype tactile stimulations on the tongue. Our exploratory study with six designers shows that our design tool supports easy prototyping without prior expertise and background in Haptics.
- We contribute results from fundamental psychophysical studies which show that the TactTongue toolkit can render diverse tactile and taste sensations. Our first study focuses on the capability of TactTongue to render various tactile effects. To the best of our knowledge, this is the first study that focuses on the qualitative aspects of tactile sensations on the tongue and provides insights into how the sensations vary across different regions. Our second experiment is a technical study that measures the touch input robustness of the device. SNR levels measured from this experiment are >15dB which shows that it can sense touch input with high robustness [12].
- Finally, we present a set of application examples demonstrating that TactTongue can be deployed in various domains, including sensory augmentation in surgery (e.g., for hands-free mode switching and real-time feedback during anatomical dissection), sensory substition for accessibility (e.g., providing real-time navigational information via tongue), and increasing immersion in XR (Extended Reality), e.g., providing real-time sensory effects on the tongue while drinking beverages in virtual experiences.

2 RELATED WORK

Integrating the human tongue in interactive systems has been explored in diverse avenues in previous literature, including as an output apparatus to control external devices and as an input surface for sensory substitution. In recent studies, electrical and thermal stimulation on the human tongue is also investigated to simulate taste sensations [62, 63]. However, much exploration must be conducted to experimentally study various aspects of the human tongue, e.g., the sensitivity of different areas to varied physical stimuli such as electrical, thermal, and tactile. Thus, it is essential to have a toolkit technology that interactive systems designers and developers can adapt to conduct safe in-situ analysis on the human tongue in different contexts. As a result, our work falls at the intersection of tongue interfaces, haptics, and the design of prototyping toolkits. This review presents related works in three areas: 1) tongue and oral interfaces in HCI, 2) sensory substitution techniques using tongue, 3) prototyping Toolkits in HCI, and (4) designing haptic experiences.

2.1 Tongue and Oral Interfaces in HCI

Several oral interfaces were developed to explore the movements of a user's tongue as an alternative input methodology to interact with computing systems, mainly for people with physical disabilities [35, 43]. More advanced implementations comprise keypad areas and mouse pad areas, instead of joystick-like controls, for

[1]https://www.wicab.com/

more precise interactions and inputs, such as controlling a mouse pointer in a computer or accurate text-typing [10, 26, 39, 54, 82, 83]. Prior research has also shown that when coupled with novel stimuli, the tongue's capability to learn interaction increases by 40%(e.g., typing, pointing, target tracking) [9, 41]. The TYTH wearable system proposes an input technology based on the relative location and interaction between the user's tongue and teeth instead of popular inductive sensors [47]. In recent work, recognizing tongue gestures for non-vocalized speech and assistive tongue gesture devices have been explored [53]. These works investigate applications beyond the text input and mouse pointer control to synthesize speech [14] and create conversations while in an articulated-head character costume [80]. Additionally, potential applications of interaction design with mobile devices through oral and tongue interfaces were investigated [11, 17]. Conversely, different areas of the human mouth have been examined as alternative output apparatuses, including the tongue and lips [27, 79, 87].

2.2 Sensory Substitution using Tongue

Sensory substitution through the use of electrotactile devices on the human tongue is a significant area that involves somatosensory stimulation. It has been extensively studied in prior literature in neuroscience and medicine [6, 28, 46, 55, 68]. Fall prevention by controlling posture and balance is a popular application area explored under sensory substitution through the human tongue [89–91]. It is shown that a user's posture and balance can be improved by delivering foot sole pressure distribution through a wireless embedded tongue-placed tactile output device. Another fascinating application of electrotactile stimuli on the tongue for sensory substitution is providing visual aids for people who are profoundly blind [7, 65, 67, 71].

2.3 Prototyping Toolkits in HCI

Toolkit research is a crucial area in the field of HCI since toolkits can "heavily influence both the design and implementation" of interactive systems [38]. Greenberg [19] defines toolkits as generative platforms designed to create new interactive artifacts. They provide easy access to complex algorithms, enable fast prototyping of software and hardware interfaces, and facilitate creative exploration of design spaces. Therefore, a lot of toolkit research focuses on reducing the barrier to entry for novice users by abstracting the underlying technical complexities of existing technologies, minimizing authoring time, and creating paths of least resistance. Prior research has contributed several toolkits for various technologies such as capacitive sensing [36, 60, 73], physiological sensing [48, 49] and for rapid prototyping of cross-device applications with smartwatches [25]. There are other toolkits that provide software and hardware support for prototyping physical user interfaces [16, 20, 24, 88].

2.4 Designing Haptic Experiences

Additionally, toolkits for prototyping haptic experiences are a major research theme that is actively being pursued in HCI and haptics research communities. Schneider et al. provide an overview of the field of haptic experience design (HaXD), highlighting challenges and opportunities in the field [74]. A variety of prototyping toolkits have been developed in HCI and haptics research communities for rendering tactile feedback. These include tools for prototyping and rendering vibrotactile effects [15, 81, 85], using sonification for prototyping vibrotactile effects in VR [13], tools that support sketching [50, 75] and leverage visual and acoustic proxies for designing vibrotactile representations [77, 78]. While vibrotactile feedback has been most extensively explored in literature, some toolkits have been developed for other actuation mechanisms. For instance, Pfeiffer et al. presented a toolkit for prototyping force feedback with electrical muscle stimulation [58]. Groeger et al. presented a design tool for customizing electrotactile feedback on 3D printed objects [22] and epidermal devices have been designed for producing tactile sensations on the body [51, 94].

A large body of work in HCI has contributed to prototyping platforms for designing tactile feedback using various actuation mechanisms. However, to the best of our knowledge, none of these can be deployed on the tongue. Furthermore, while there is literature in Neuroscience and biomedical engineering communities on designing electrotactile interfaces for the tongue, they do not contribute a prototyping platform. This makes it challenging for novice users and designers to map the low-level electrical engineering parameters to higher-level tactile feedback design.

The next section presents the design requirements that are unique to the tongue and how our prototyping platform enables rapid and seamless prototyping of tactile effects on the tongue.

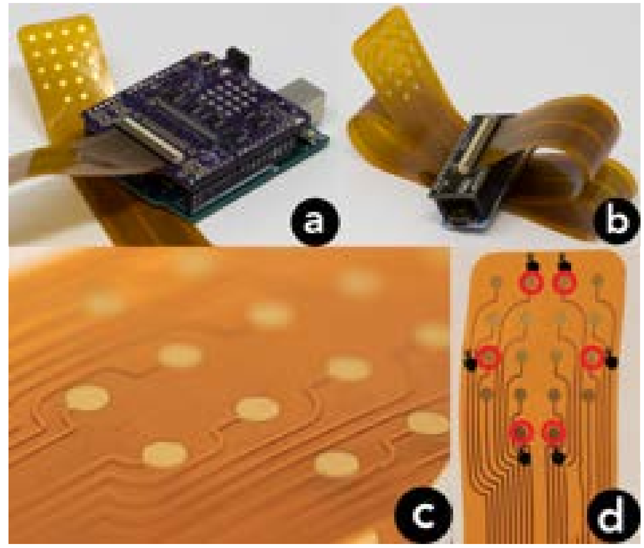

Figure 2: TactTongue hardware setup: (a) works with an Arduino Uno to generate pulses for electrotactile stimulation (b) for supporting easy integration into wearable and XR applications we engineered a miniaturized version of the shield to work with the Arduino Nano (c) exposed electrodes for electrical contact with the skin and insulated traces (d) electrode array with 2mm diameters and 4mm interelectrode spacing. Electrodes highlighted in red are touch-sensitive.

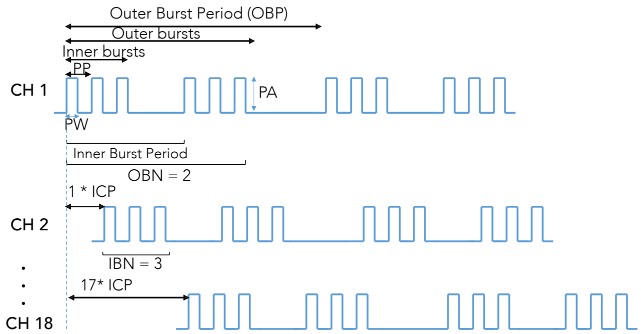

Figure 3: The waveform output used for generating the tactile sensations. They are grouped as bursts of pulses and the parameters shown in the illustrations can be modified to achieve desired sensations.

3 PROTOTYPING ELECTRO-TACTILE STIMULATIONS ON THE TONGUE

We developed our prototyping toolkit by analyzing the literature on neuroscience and surgery. These domains have extensively experimented with tactile stimulation on the tongue for surgical operations. However, these designs are tailor-made for surgical applications and require extensive expertise in hardware design, electrical engineering, and haptics, prohibiting their deployment for applications in HCI. Our prototyping toolkit is built on these solid fundamental principles, and we also developed a design tool to facilitate rapid prototyping of tactile stimulations on the tongue.

3.1 Design Requirements

There are several challenges that are very specific to electrotactile stimulation on the tongue. Below we highlight the most important design requirements:

3.1.1 Stimulation Current. Compared to electrotactile stimulation on other regions of the body, the tongue requires very low current levels. For instance, prior work reported that a current of $[0.96 - 1.83]mA$ was required to produce electrotactile stimulation on the finger [94]. However, for the tongue, this range goes down drastically (approximately by two orders of magnitude) with currents reported to be in the range $[20 - 100]\mu$A [63]. Hence the prototyping hardware should be able to deliver such low-level currents.

3.1.2 Stimulation Parameters. For electrotactile stimulation on the tongue, multiple biphasic pulses grouped in short bursts result in comfortable, effective electrotactile stimulation [28, 30, 87]. The characteristics of pulses play a more vital role in determining the type of stimuli that is to be rendered [21, 28, 69]. For instance, longer pulses may preferentially activate the smaller fibres (Aδ, C) that are responsible for pain sensations rather than the fibres (Aβ) that subserve tactile sensations [21]. Based on these observations, prior work has extensively used the parameters of PWM (pulse width modulation) for controlling perceived sensations on the tongue [28, 45, 46]. In line with this prior work, instead of using parameters such as current and voltage, the PWM properties as the stimulus parameters were used for TactTongue.

3.1.3 Variances in Sensitivity Across Tongue. The tongue is one of the more peculiar organs that have varying sensitivity levels. This refers to the variation in the concentration of taste receptors and the variation in the mechanoreceptors. Figure 7, illustrates the taste perception capabilities at different regions on the tongue and the varying levels of mechanoreceptor concentration that influence tactile perception. Hence a design requirement is that the users should be able to precisely manipulate and control the stimulation intensity levels at different regions on the tongue. This will facilitate the rendering of diverse and expressive tactile effects.

3.1.4 Flexible Form Factor. Prior work in HCI has majorly focused on tongue interfaces that are handheld [44, 63]. However, there are many advantages to having a device that has a flexible form factor. Firstly, it allows for hands-free interaction. This is crucial in the areas of accessibility where a user with motor impairments might have restricted motor movement, and the device can be used for providing targeted tactile feedback. Similarly, in XR applications, the user's hand is typically busy with gestural interaction or holding controllers. Hence in such scenarios, a flexible device placed in the mouth can render targeted haptic feedback.

3.1.5 Precise Control of Spatio-Temporal Parameters. The human tongue has high tactile sensitivity, and the sensitivity also differs across the tongue. Hence, a stimulus that is perceived as strong in a specific region can be perceived as weak in another region. This becomes very crucial when highly articulate spatiotemporal patterns need to render. Therefore, for any pattern that the user needs to render, they should have precise control over the intensity, duration, location (which is determined by the position of a given electrode), and PWM parameters.

3.2 Hardware Implementation

The tongue is a highly sensitive (i.e., susceptible) organ. Hence, the tactile stimuli must be carefully designed to ensure that only the fibres responsible for tactile sensations are triggered. A commonly used approach is to design stimuli as a train of pulses [6, 31, 87]. Designing stimuli in the form of pulses has many advantages: (i) firstly, since the duration of pulses is short, they majorly activate the fast adapting non-pain receptors (ii) the pause between the pulses with adequate timing will also reduce the sensory fatigue and keeps the tongue from becoming numb very quickly. (iii) thirdly, the period/pause between the pulses can be used for programming diverse tactile effects, and (iv) Finally, from engineering and implementation perspectives, most microcontroller platforms (e.g., Arduino) have the ability to generate these pulses through pulse-width modulation resulting in simple yet robust hardware design.

3.2.1 Electrode Array. The electrode array consists of a flexible PCB with 18 electrodes. The size of each electrode is 2 mm (diameter) with an inter-electrode spacing of 4mm, as shown in Figure 2. The electrodes are exposed while the traces are insulated to ensure stable electrical contact and precise stimulations.

3.2.2 Pulse Generation. Our implementation is based on the fundamental experiments that have been reported in the field of neuroscience and surgery [28, 31]. These devices use an RC network (i.e., a resistor–capacitor circuit) with high impedance to ensure minimal net charge flows through the tongue. The hardware consists of Arduino Uno/Nano shields that send low-current pulses to an 18-electrode array (Figure 2(d)).

Figure 3 illustrates the design of the waveforms. The configurable parameters for controlling the stimuli are listed below:

Pulse Period (PP) - this is the period between the individual pulses within an inner burst. This is usually in microseconds and can be manipulated with Pp and IN to change the intensity of the sensation.

Pulse Width (PW) - this is the width of each pulse in microseconds. Manipulating this parameter along with the pulse period modifies the inner burst which influences the intensity of sensations [28].

Inner Burst Number (IBN) - refers to the number of pulses in the inner burst. For instance, in Figure 3 the inner burst number is 3, signifying that there are 3 pulses within the burst.

Inner Burst Period (IBP) - refers to the inner burst period in microseconds. It determines the delay between successive inner bursts.

Outer Burst Number (OBN) - Outer burst number is the group of inner bursts. For instance, in Figure 3 the outer burst number is 2, which signifies that there are two inner bursts within the outer burst.

Inter-Channel Period (ICP) - ICP refers to the inter-channel period. This parameter can be used for manipulating timing parameters for directional patterns.

To summarize, individual pulses of width (PW), repeating with a period (PP), are grouped into inner bursts. The number of pulses in each inner burst is defined as the Inner Burst Number (IBN). Since the neural membrane on the tongue acts as a leaky integrator (parallel RC network), the net charge resulting from all these individual pulses summate to cause membrane depolarization, i.e., the polarization of the underlying cells changes due to these stimuli. Usually, this happens only if the charge accumulation goes beyond a specific threshold [3]. This threshold depends on several subjective factors, including the membrane properties, fibre orientation, size and geometry of the electrodes, and the effective RC time constant (typically estimated to be around 70-900μS) [64].

3.2.3 Circuitry Implementation. The stimuli design based on waveform generation enables the hardware implementation to be more widely accessible since most microcontroller platforms (e.g., Arduino) support pulse width modulation. The hardware is built as a shield for Arduino Uno and Nano microcontroller boards and builds on the designs proposed in prior work [28, 46]. While some of these designs have been proposed for Arduino Uno[2], they are no longer available. Secondly, the designs are also very complicated (e.g., requiring ~75 components) which necessitates a significant level of electrical engineering expertise for component sourcing and manufacturing. Therefore, we undertook the task of redesigning and reverse-engineering the entire hardware. Our new optimized design incorporates nearly 50% fewer components compared to previously designed shields. Additionally, our design for a smaller footprint microcontroller (Arduino Nano) enables TactTongue to be deployed in wearable applications and also allows for integration into commercial devices such as HMDs.

In addition to the digital pins (D2-D13), we also used the analog pins (A0-A5) on Arduino as digital pins[3]. For precisely controlling the timing parameters for the pulses, all the digital pins are connected as inputs to the individual electrode channels through an RC (R = 1MΩ, C=0.1μF) network. The circuitry is shown in Figure 5. Furthermore, to accelerate replication, we provide all the source code, firmware, and schematics of our implementation [4].

3.2.4 Capacitive Touch Sensing. Using the RC network also enables capacitive touch sensing on the electrodes. Analog pins are used [A0-A5] to sense touch. Initially, all of them are set to high and then used Arduino's `analogread` function to read the input values. When the tongue makes contact with one of the touch electrodes, it shunts some of the charges to the ground, which can be used for detecting touch events. To enable directional input, the six analog pins are connected to electrodes in four different directions: bottom (2X), top (2X), left (1X), and right (1X), as shown in Figure 2(d).

3.3 Software Design Tool

We contribute a design tool to abstract the designer from low-level technical parameters for rendering highly articulate tactile sensations. The tool's design is principled on the design requirements as described earlier. Figure 4 shows the overview of our design tool.

3.3.1 Precise Control of Individual Electrodes. The TactTongue tool allows designers to control the stimulation parameters for each electrode precisely. First, the designer can choose an individual electrode by clicking it. Then, he can individually adjust the parameters (pulse period, inner burst number, outer burst number, inner burst period, and pulse width).

3.3.2 Precise Control of Spatio-Temporal Patterns. To ease the prototyping of spatiotemporal patterns, the TactTongue tool offers a large set of presets that include directional patterns (e.g., Up🡡, Down🡣, left🡠, right🡢) as well as shape patterns(see Figure 4(b)). Moreover, TactTongue employs a designer-in-the-loop philosophy. To further fine-tune the stimulus parameters for each of the directional patterns, the designer can choose the order of stimulation of the electrodes (Figure 4 (c)). Once the order is determined, they can also adjust intensity values for each of the electrodes through the "Intensity" panel (Figure 4(a)). In the example shown in Figure 4, the designer selects the "square" shape (highlighted in pink), then adjusts the intensity levels of each of the electrode such that the electrode present at the lateral dorsum of the tongue have intensity values since the sensitivity of that region is less when compared to the tip of the tongue.

3.3.3 Sensation Presets. To enable rapid prototyping in diverse application scenarios, the TactTongue design tool presents a set of presets for rendering diverse tactile sensations. The parameters for these have been derived from the results of our study (which will be introduced in the next section). In addition to the sensation presets, we also have presets for rendering taste. Because tactile sensations

[2]https://www.sparkfun.com/products/retired/15897

[3]The analog pins in Arduino can be used as digital pins: https://www.arduino.cc/reference/en/language/functions/digital-io/digitalwrite/

[4]https://github.com/difflab-ucalgary/TactTongue

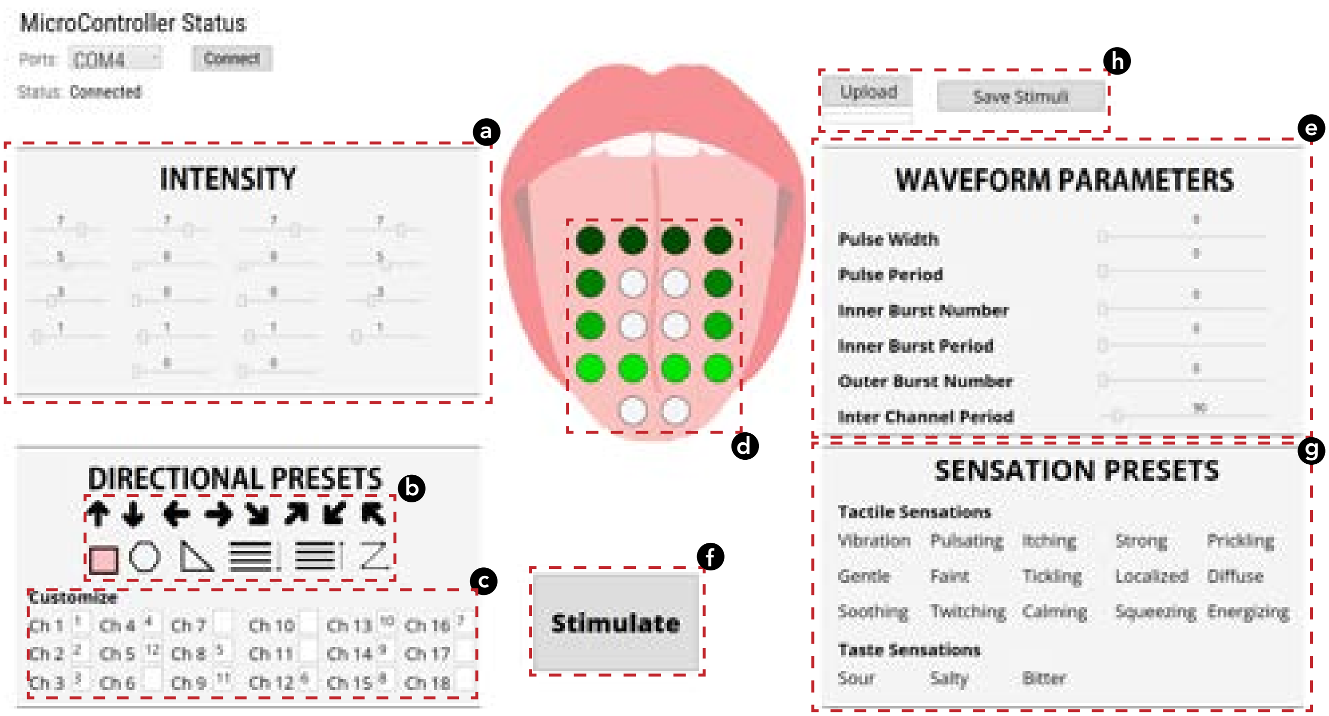

Figure 4: Design tool for prototyping electrotactile sensations and patterns on the tongue. (a) panel for adjusting the intensity levels of each electrode. (b) presets of rendering directional and shape patterns (c) toolbar to customize the order of rendering for each shape (d) visual representation of the electrode array. The colour indicates the intensity levels set for each of them e.g., dark green indicates a higher intensity level. (e) toolbar for fine-tuning the waveform parameters (f) button click sends the command to the hardware (g) presets for rendering sensations and tastes on the tongue (h) parameters can be saved or uploaded into the tool.

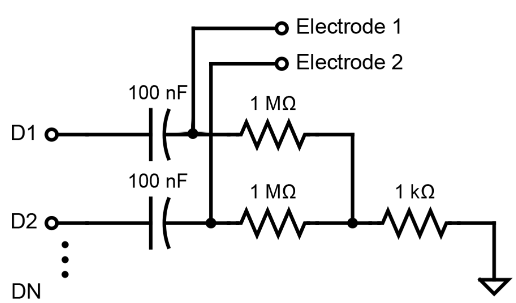

Figure 5: Circuit representation of the shield. "D1, D2...DN" are digital pins of the control board and "Electrode 1,2" are the respective electrodes on the tongue electrode array.

are highly subjective, we also provide the designer with options to fine-tune or add custom presets for sensations. The designer can do this by manipulating the waveform parameters (Figure 4(e)).

3.3.4 Exploring and Sharing Experiences. TactTongue enables saving multiple patterns and quickly switching between them for quick comparisons, as in Figure 4(h). Electrotactile patterns can also be exported and saved as a JSON file for remote research collaborations. For instance, using TactTongue, the designer can load a pattern designed by a colleague, experience it, and save it as a preset if required.

3.3.5 Implementation. We implemented the tool as a WPF (Windows Presentation Framework) application. The tool communicates with the Arduino via serial port at a baud rate of 9600.

3.4 Study 1: Formative Evaluation

We conducted a formative design activity with six designers to understand if the TactTongue interface can help designers rapidly prototype electrotactile sensations. Our evaluation strategy is based on prior work, where qualitative reflections from designers have been very insightful for understanding the design of haptic design tools and prototyping toolkits [38, 60, 95]. All the users in our experiment had expertise in design, haptics, and HCI.

3.4.1 Task. The experiment took place in a quiet room. For hygiene purposes, we had multiple flexible electrode arrays. Each participant was given a new device. The experimenter demonstrated the TactTongue interface and the control hardware. Once the experiment was completed, the devices were cleaned and thoroughly sanitized. We used standard cleaning procedures used for sterilizing dental tools [37]. Following each use, the electrode array was carefully sterilized using isopropyl alcohol swabs (70%).

We had two conditions for the experiment: (i) Arduino sketch-based setup and (ii) TactTongue interface. In the first condition, the participants administered the device on their tongues and manipulated the parameters in the default Arduino sketch. After that, they were free to program various sensations. In the second condition, the participants used the TactTongue interface to prototype the sensations. We counterbalanced the order of presentation of these conditions. After experimenting with each condition, we elicited reflections from the participants based on their experiences.

3.4.2 Results. Overall, our results show a high preference for using our design tool.

Stimulation Parameters. Even though our participants have a background in HCI, interaction design, and haptics, they did not understand how the parameters influence the stimulation waveforms. Without the software tool, they had to understand the details of the stimuli design and then write /modify the Arduino sketch to render a stimulus. Our software design abstracts these details from the designer and provides intuitive controls for manipulating the parameters for each electrode.

Importance of Presets. One of the key features that the participants appreciated was the presets for rendering directional and tactile sensations. Because the tool offered presets, participants could instantly render and experience tactile feedback.

Resetting the Arduino. In condition 1, participants had to manually flash the code for every change they wanted. All our participants disliked this. With our design tool, the serial connection to the app is retained, thus no need for re-flashing the code for every minor change in the stimulus.

Errors in choosing the Electrodes. In condition 1, participants had to choose the electrode by mapping it to the appropriate array index in the Arduino sketch. For instance, if the participant had to toggle the state of the 12th electrode, they had to change the accurate array index in the Arduino sketch. Unfortunately, this can be error-prone and not scalable for much denser electrode arrays.

4 STUDY 2: QUANTIFYING SENSATIONS

An extensive body of literature has studied the psychophysics aspects of tactile sensitivity on the human tongue. These include the measurement of absolute thresholds, 2-point discrimination tests [87], directional pattern recognition, and taste perceptions.

To the best of our knowledge, in this experiment, we, for the first time, investigate the qualitative aspects of electrotactile stimulation on the tongue. We aim to understand the intricate interplay between the tactile and taste sensations that can be produced through electrotactile stimulation. *How do sensations transition from tactile to taste?*

For the first task, our research question is: *What are the range of sensations (including tactile and taste) that can be produced on the tongue through electrotactile stimulation? How do these sensations vary across the five major regions of the tongue?* . Our experiment has been designed based on prior work, which elicited qualitative feedback for electric muscle stimulation [59] and vibrotactile stimulation [81].

Prickling	Gentle	Pulling	Vibrating	Pulsating	
Itching	Forceful	Stinging	Soothing	Twitching	
Hurting	Squeezing	Localized	Diffuse	Jabbing	
Energizing	Bitter	Salty	Sour	Irritating	
Sweet	Umami	Tickling	Faint	Strong	Calming

Table 1: Terms used by participants to describe the sensations they had in the first study phase. They could pick any number or none of them.

4.1 Method

4.1.1 Stimuli Selection. The main challenge in quantifying the sensations is the vast parameter space that exists when creating stimuli. Since multiple parameters (pulse width, period, inner bursts, and outer bursts) influence the waveform patterns, which affect the sensations, it is highly impractical to sample the entire parameter space. Therefore, instead, we meticulously chose a limited set of stimuli that can elicit diverse sensations [59]. These were chosen from prior work, which reported that PW and inner burst structure (PP, IBN) could influence the intensity of stimulation [18, 69]. In addition, manipulating OBN and IBP can change the perceived quality of the electrotactile sensation, as well as its ability to convey spatial information [1, 23, 29]. These non-intensive perceptual quality changes have been loosely described as tactile "colours" because they are readily discernible, although not nearly so much as for colour vision [1, 33]. For example, increasing pulse rate typically results in percept changes from pulsatile to vibration to pressure. In contrast, pulse width and burst structure can affect the comfort of the percept (vibration/tingle vs. pinprick) [32, 72]. Based on these observations and from our pilots, we sampled stimuli waveforms with a good mix of variations in the inner burst structure and the outer burst number.

4.1.2 Participants. We recruited 10 participants (mean age: 27.8, sd: 3.47, 5 Female). We fabricated multiple arrays, and each participant was provided with a fresh device. All the arrays were sanitized and cleaned before the experiment. Subsequently, it was thoroughly rinsed with clean water and cleaned with soft tissue. The study has been approved by our institutional review board, and the participants were compensated with $15 USD.

4.1.3 Procedure. We counterbalanced the order of presentation of the tongue regions. The experimenter carefully aligned the electrode array so that most electrodes covered the target region on the tongue. To ensure that the correct region was being stimulated, we rendered a set of test stimuli and elicited participant feedback on the region they felt the stimuli. The participants were shown the sketch of the regions on their tongues and were asked to highlight the region they felt the stimuli. Once the target region was confirmed, each participant was presented with a randomized set of stimuli. After each trial, participants elicited the sensations they felt. In line with prior work, participants chose from a set of sensations (Table 1). In addition, we also added basic tastes (sweet, sour, bitter, umami, and salty) to this list. We randomized the layout of the terms for each trial to avoid ordering effects. Participants were instructed to choose any number of terms that they felt were relevant to the experienced stimulus. They could move on without selecting any

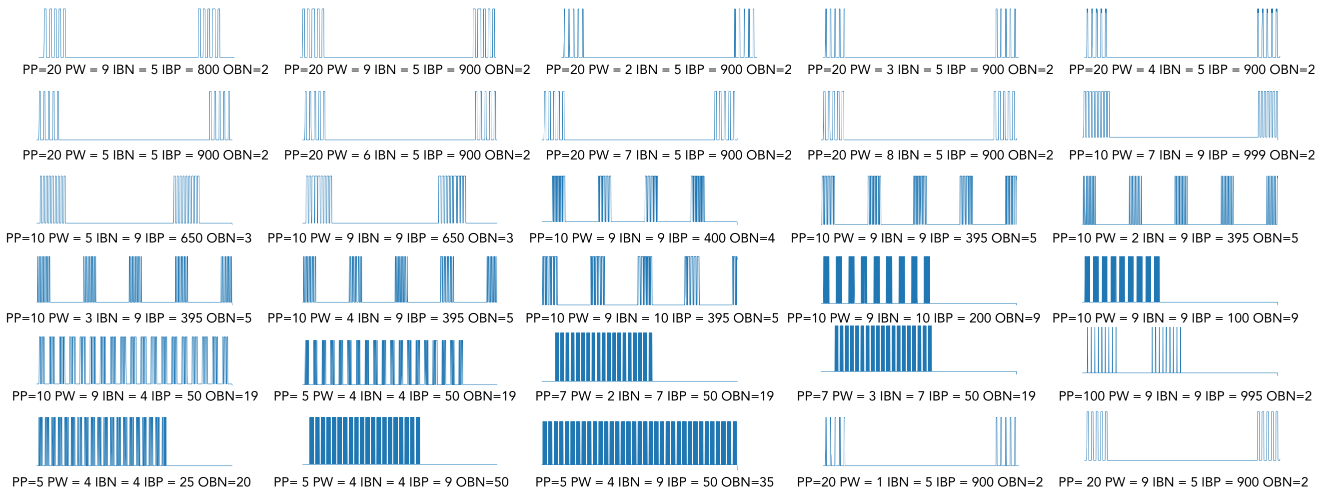

Figure 6: Stimuli waveforms used in our study. By varying the inner burst number (IBN), outer burst number (OBN), pulse width (PW), and pulse period (PP), we designed a wide range of waveforms to understand how these can influence the sensations on the tongue. Note: since the pulse periods are very small (a few μS), in a few waveforms they appear to be merged.

term if they did not feel anything. There was a 5s interval between each trial to ensure that the receptors returned to their normal state. This period is longer and a more conservative estimate than the interstimulus intervals employed in previous work [87]. Participants were free to take breaks during the experiment. For each region, we randomized the order of the stimuli. There were a total of 30 (stimuli) × 5 (regions) × 10 (participants) = 1500 trials recorded. The entire experiment took 90-120 minutes.

4.2 Results and Discussion

Overall, we noticed that TactTongue could produce a wide range of sensations. We collected a total of 1921 responses from 10 participants (5 Female and 5 Male). Based on this data, we performed a series of analyses to understand how the stimuli parameters can influence the sensations.

4.2.1 Sensations Vary Across Regions. The first key takeaway is that the sensations produced vary across the regions of the tongue. This is expected because the human tongue has varying receptor concentrations across the regions. The same holds for taste receptors. After collecting all the responses, we grouped them according to region. Then we selected the six best sensations for each of the regions of the tongue. Figure 7 shows the main sensations that were elicited in each of the regions of the tongue. It can be noticed that Tip has the highest diversity with regard to sensations. This is understandable because of its high sensitivity. However, the back dorsum of the tongue produces the least number of sensations. The majority of the sensations elicited were `Faint`. This is because of poor tactile sensitivity. We also noticed that sensations that are typically considered `Strong` or `Prickling` at the tip of the tongue were felt as `Gentle` and `Faint` at other regions of the tongue. A key design implication for this is to render spatiotemporal patterns. While rendering spatiotemporal patterns such as directions or shapes, having uniform intensity for all the electrodes can break the shape

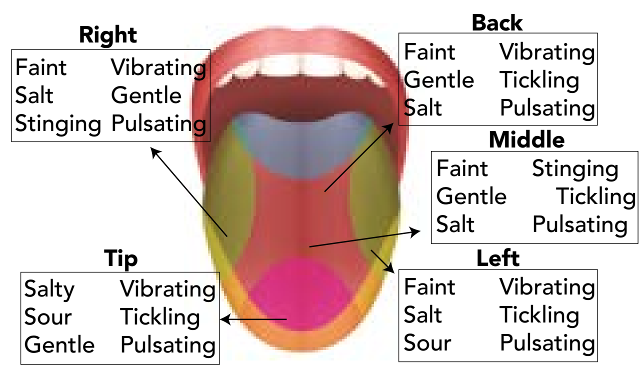

Figure 7: Distribution of the most commonly elicited sensations are each tongue region.

perception because of the inherent diversity in the tactile sensitivity of the tongue. We recommend setting adaptive intensity levels based on the location of the electrode on the tongue. This could be a promising approach as previous work showed that the back of the tongue is less sensitive to electrotactile stimulation [66]. To understand the influence of the region of the tongue on the distribution of sensations produced, we conducted a Friedman's test. Results showed that there is a significant difference (X^2(4)=20.26, p<0.001) in the sensations across the five regions of the tongue. Nemenyi pairwise post-hoc tests showed that there is a significant difference between the following pairs: Tip-Back (p = 0.001), Middle-Back (p=0.005). There was a strong but not significant difference between Back-Left (p=0.1) and Back-Right (p=0.1) pairs.

4.2.2 Taste Sensations. For rendering taste sensations, the left side of the tongue is more suitable. To understand how TactTongue produces taste sensations across all the regions of the tongue, we calculated the total percentage of all the taste responses for all the

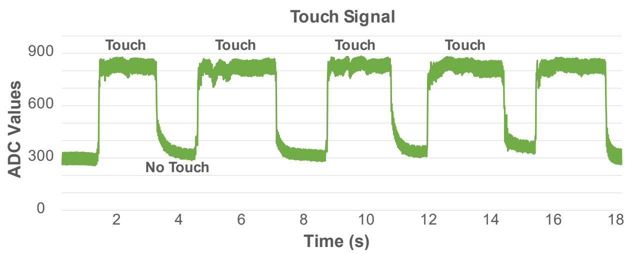

Figure 8: Touch sensing with the Tongue. By leveraging the RC network, capacitive touch sensing can also be implemented through the six analog pins. This is the raw signal when the tongue touches one of the touch electrodes.

regions. Among the taste sensations `Salt` is the most frequently elicited sensation followed by `Sour`. It is also interesting to note that the left region of the tongue produced the most number of taste sensations with a predominance of `Salt` and `Sour`. `Umami` was the least elicited response and only 2 participants reported these sensations. This could be due to the fact that it is not a well-known sensation and it was difficult for the participants to map it.

Overall, these results indicate that TactTongue can produce highly diverse sensations. It is also noteworthy that a few of the taste sensations can also be rendered.

5 STUDY 3: MEASURING TOUCH SNR

Since TactTongue can also function as an input device, we were interested in understanding the robustness of the touch input it supports. Our experiment design is based on prior work which reported technical experiments to measure touch SNR with sensors placed on the body [34, 40, 52, 92, 93].

We recruited 8 participants (mean age:29.7, sd:2.1, four females). The participants were escorted to a silent room and were introduced to the touch-sensing functionality. In the training phase, they were free to test the functionality by performing touch input with the tongue.

We developed custom software in WPF, which randomly highlighted one of the six touch electrodes. Then, participants had to perform a touch input on that specific electrode. When the touch event on the specific electrode is detected, a virtual button turns green, and participants maintain the touch contact for two seconds. For each touch electrode, we collected five trials, resulting in 30 trials per participant. The data for all the trials was logged into a CSV file. The entire experiment took approximately 20 minutes.

5.1 Results

Figure 8 shows the raw touch signal for touch input performed on a single electrode. We calculated the SNR for touch input using the below formula [12]

$$SNR = \frac{(\mu_s - \mu_b)}{\sigma_s} \quad (1)$$

where μ_s and μ_b are the mean value when pressed and mean value when not pressed respectively. σ_s is the standard deviation of the signal.

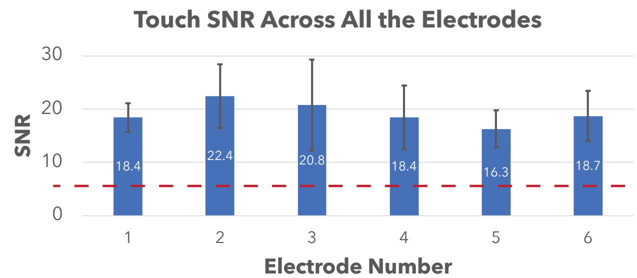

Figure 9: SNR levels measured for each touch electrode across all the participants. The red dashed line indicates the minimum required SNR (7dB) for robust touch sensing [12].

Figure 9 shows the SNR levels measured for each touch electrode. Average SNR levels are high and well above the minimum SNR levels required for robust touch sensing [12]. The lowest SNR level was 11.33 dB for Electrode No.2. This is also higher than the minimum required threshold. These results indicate that TactTongue can touch input with high robustness.

6 APPLICATIONS

To demonstrate the versatility of TactTongue, we present application cases in diverse application contexts.

6.1 Sensory Augmentation in Surgery

The seminal work by Paul Bach-y-Rita has demonstrated sensory substitution through tactile feedback on the tongue [5, 6]. Tactile feedback on the tongue provides an ideal opportunity for sensory augmentation and has been previously explored for guiding a needle during a surgical procedure [68]. To better understand how TactTongue can be deployed in the context of surgery, we conducted semi-structured interviews with a surgeon and identified potential use cases. Then, after implementing our application demonstrators, the surgeon tested them and evaluated their feasibility.

6.1.1 Notifications for Mode Switching with Busy Hands. Surgeons routinely use electrocautery tools for cutting and coagulating tissues. The tool is a handheld device with a rocker button to switch between the modes. The feedback for switching between modes is typically delivered through audio cues, which can be easily lost due to other noises from diagnostic equipment in an operation theatre. To address this problem, our expert participant suggested that the tool's mode could be presented as tactile feedback on the tongue instead of audio cues. In our prototype, the electrocautery tool's cut and coagulation buttons triggered different stimulus patterns on the tongue (Fig. 10(d)). Our participant could successfully detect the mode even with his eyes closed.

6.1.2 Rendering Spatial Relationship between surgical tools and critical anatomical structures through Tactile Feedback. A surgeon often wants to avoid cutting too close to major vessels during an anatomical dissection. Imagine a traditional navigation system that visually displays the distance between the tip of the dissection tool and the vessel. However, this would require the surgeon to look away from the surgical site to see the display. As a solution, our participant proposed that we display the tip-to-vessel distance on the tongue. In this prototype, the stimulus frequency and intensity should be increased as the tip gets closer to the target. When the tip was dangerously close, the intensity should be very strong for the surgeon, suggesting aborting the operation.

To simulate this scenario, we developed a prototype in the Unity game engine that tracks the position of the dissection tool using a laptop webcam and a Vuforia marker. The Unity code then sent serial USB commands to the Arduino board that controls the tongue electrodes. Our participant could describe how far the dissection tool was and if it was getting closer or farther even with his eyes closed (Fig. 1(e)).

6.2 Sensory Substitution for Accessibility

Touch sensing enabled through TactTongue can be highly beneficial in many scenarios. For instance, in XR, where hands typically perform mid-air interactions or hold controllers, touch input through the tongue can provide another interaction modality. The same scenario applies to accessibility, where motor-impaired users can use their tongues as input devices. In this example, we developed a game in Unity where a user guides a ball to a given target through directional gestures on TactTongue.

6.3 Increasing Immersion and Multi-Sensory Experience in Extended Reality (XR)

Recent research in HCI has contributed several approaches to increasing realism in XR. These include novel haptic devices [84], chemical haptics [42], and VR olfactory interfaces [4]. Inspired by this, we prototyped a drink simulator, in which, when a VR character drinks a beverage, we render the flow of the liquid on the tongue through one of our directional presets (Figure 1(c) and video figure). Also, we can simulate the effects of different beverages, such as soda and lemonade.

6.4 Sensory Augmentation for Robotic Teleoperation

In contrast to non-robotic surgery, most surgical robots do not allow a surgeon to feel how much force they exert onto the tissue with their hands. Our expert reported that surgeons use visual cues, such as tissue deflection or discolouration, to gauge exerted force indirectly. We integrated a force-sensing-resistor film sensor onto the grasping tool of an Intuitive da Vinci[5] surgical robot. We mapped the tongue display's stimulus intensity to the force measured (Figure 10 (a)) by the film sensor. Our expert found the prototype to be surprisingly effective. He reported that it was easier for him to gauge the force level of his grasp with tactile feedback on the tongue. Furthermore, he also noted that it outperformed conventional visual cues (lower latency). Our expert suggested that TactTongue would be beneficial for training (to help novice robot operators estimate how much force they exert onto the tissue) and also for actual clinical use.

[5]https://www.intuitive.com/en-us/products-and-services/da-vinci

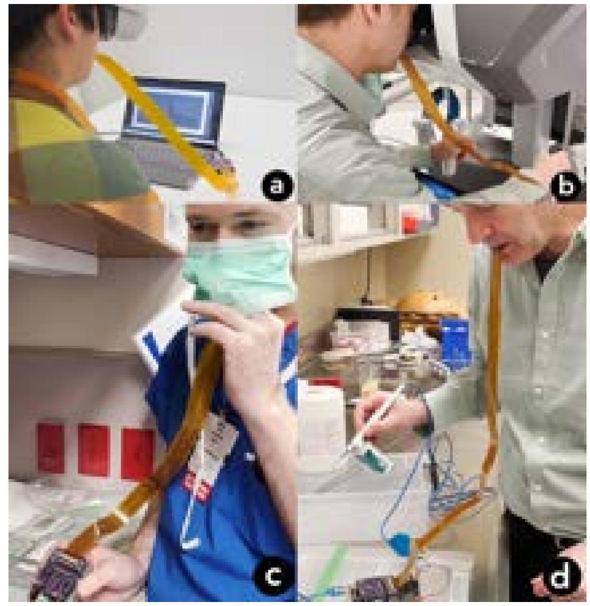

Figure 10: Application Scenarios for TactTongue: (a) Hands-Free Input for Accessibility: The user controls a ball with directional gestures with the tongue. (b) Robotic Teleoperation: The surgeon operates a surgical robot coupled with TactTongue. The force exerted by the gripper is rendered onto the tongue. (c and d) in surgical applications where a surgeon can be provided precise haptic feedback when hands are busy and other sensory organs such as eyes and ears are occupied.

7 DISCUSSION, LIMITATIONS AND FUTURE WORK

7.1 Overstimulation and Sensory Fatigue

Our brains execute metamodal computations and tasks using an integrated network known as the metamodal organization of the brain [56]. This hypothesis believes that brain organization is not necessarily organized by sensory modality but rather by the computational or functional task being carried out [61]. As a result, cross-modal associations can arise when two sensory forms overlap, in line with the metamodal hypothesis. Because the tongue is a multi-modal organ (it has taste receptors and tactile mechanoreceptors) such cross-modal associations can be triggered through TactTongue. Our studies were majorly focused on quantifying the sensations. However, the results open new research avenues for deeply studying the cross-modal aspects and the multi-sensory associations that can be formed by merging the tactile and taste sensations on the tongue with other sensory stimuli such as visual/auditory stimuli. Our open-source toolkit can enable the research community to explore these unexplored research questions, accelerating contributions to understanding the metamodal and cross-modal associations.

Secondly, because our tongue has a rich network of taste and tactile receptors, overstimulation is possible. Since our trial durations were very short and we had sufficiently long inter-stimuli intervals, our participants did not notice any overstimulation. However, we do believe that future studies should focus on the overstimulation aspects (e.g., which region on tongue is predominantly susceptible to overstimulation, the duration of stimuli which can result in overstimulation, the stimuli waveform, etc.)

7.2 Individual Variations in Sensitivity

The inherent tactile sensitivity of the tongue varies from person to person. Similarly, personal habits can also influence sensitivity. For example, smokers have highly reduced tactile sensitivity on the tongue. Although we did not have smokers in our studies, these external factors should also be considered when designing tactile feedback for the tongue.

7.3 Application Scenarios

Preliminary interviews and demonstrations with the surgeon were highly insightful as they opened up a vast space to research tactile feedback mechanisms while performing surgical operations. There are classical HCI-related constraints in such environments (e.g., busy hands, audio and visual information overload, and the need for not distracting the user). In such cases, tactile feedback on the tongue is highly promising. However, an in-depth longitudinal study with multiple surgeons must be conducted to fully understand the opportunities and limitations of TactTongue for surgical applications.

7.4 More Fine-Grained Sensations

In our study, the participants were asked to choose from a set of sensations. We chose this approach because it has been well-established in the literature and has been used several times in HCI literature to elicit qualitative feedback for haptic devices. However, our participants informed us that the words presented in the list were not adequate. In several cases, they elicited more granular feedback. For instance, P8 informed us that one of the sensations was `metallic`. Similarly, P7 felt that one of the sensations was similar to a fizz you experience on the tongue when you drink soda. Future work should revisit how we measure and elicit qualitative feedback, especially in the context of the tongue where there is a lot of overlap and mingling between the tactile and taste sensations.

7.5 Sensing Touch With Teeth

While we conducted our study by placing TactTongue on the hard palate region, another approach would be to have the electrodes exposed outwards (as opposed to being in contact with the tongue). Then, touch input can be performed by teeth, similar to tactile buttons that teeth can press. However, future studies should investigate this interaction modality in detail.

7.6 Integration into XR Environments to study multi-sensory experiences

One of our application scenarios demonstrates the multi-sensory experience that can be rendered through TactTongue. Future studies should investigate how to create illusions of beverages with water and TactTongue. These can be integrated into XR environments to expand the multi-sensory experience further.

7.7 Support for Other Microcontroller Platforms

Currently, our hardware platform is designed for Arduino Uno and Arduino Nano. However, we are working on designing the hardware in smaller, more compact wearable form factors.

8 CONCLUSION

To summarize, we presented TactTongue, a toolkit that enables rapid prototyping of tactile sensations on the tongue. By using an Arduino Uno-compatible shield, we can generate a wide range of stimuli for rendering diverse tactile stimulations on the tongue. Our software design enables the prototyping of directional and shape patterns, while also providing the designer with the freedom to tweak individual waveform parameters. Our studies show that (1) designers prefer and successfully could render tactile sensations on the tongue (2) TactTongue produces diverse sensations on the tongue and (3) can sense touch input with high robustness. To summarize, we believe that TactTongue will open new opportunities to deploy tongue interfaces and has broad implications for designing interfaces that incorporate the tongue as a sensory organ.

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