Arata Jingu University of Chicago aratajingu@uchicago.edu Yudai Tanaka University of Chicago yudaitanaka@uchicago.edu Pedro Lopes University of Chicago pedrolopes@uchicago.edu



Figure 1: LipIO enables the user's lips to be used *simultaneously* as an input *and* output surface. It supports eyes- and hands-free interactions via (a) electrotactile stimulation as output and (b) capacitive touch as input. We demonstrate a range of practical applications, such as (c, d) I/O for controlling appliances (e.g., a smart door or an e-bike's GPS and lights), (e) outputting the state of an interface (e.g., feeling the output of a guitar tuner rather than seeing it), and (f) rendering a simple game entirely on the lips (e.g., whack-a-mole).

ABSTRACT

Abstract. We engineered LipIO, a novel device enabling the lips to be used simultaneously as an input and output surface. LipIO comprises two overlapping flexible electrode arrays: an outward-facing array for capacitive touch and a lip-facing array for electrotactile stimulation. While wearing LipIO, users feel the interface's state via lip stimulation and respond by touching their lip with their tongue or opposing lip. More importantly, LipIO provides co-located tactile feedback that allows users to feel where in the lip they are touching-this is key to enabling eyes- and hands-free interactions. Our three studies verified participants perceived electrotactile output on their lips and subsequently touched the target location with their tongue with an average accuracy of 93%, while wearing LipIO with five I/O electrodes with co-located feedback. Finally, we demonstrate the potential of LipIO in four exemplary applications that illustrate how it enables new types of eyes- and hands-free micro-interactions.

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CCS CONCEPTS

• Human-centered computing → Haptic devices.

KEYWORDS

Haptics, lips, tongue, on-skin interface

ACM Reference Format:

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1 INTRODUCTION

Our eyes and hands are the primary way many users interact with their environment. As such, it is common for users to find themselves in many everyday situations where their eyes and/or hands are *occupied* and *not available* to interact with interfaces. To tackle this, researchers have focused a tremendous amount of effort on engineering eyes-free and/or hands-free interfaces that provide users with *both* input and output (I/O) capabilities. Not only do these interfaces provide users with an alternative method to control an interface when their eyes and/or hands are occupied, but these can also provide a degree of accessibility to those that cannot interact via eyes and/or hands. One popular and mainstream example are speech interfaces with both I/O channels in the same auditory modality [45]. More recently, researchers have been exploring new approaches that push this eyes-free I/O beyond the auditory modality. These efforts are useful since sound-based interfaces are

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susceptible to noise [37, 45, 46] and prevent users from hearing important sounds in their surroundings. These recent approaches include eyes-free gesture-I/O [23, 50] and eyes-free muscle-I/O [9, 36, 40]. While they realize eyes-free interactions, they rely on the user's *interaction via their hands*. As such, these are unsuitable for any everyday situation where the users' hands and eyes are occupied with a primary task.

As an alternative to the more traditional modalities that can often be overloaded in everyday situations (as is the case of a user's eyes, hands, or ears), researchers have explored mouth-based interfaces. The most advanced implementations of these take the shape of intraoral-based devices-they reside inside the user's mouth, typically atop the user's tongue or roof of the mouth. These have been used for tongue/teeth input [10, 14, 16, 30, 32, 64] but also for output, e.g., electrical stimulation on the tongue [24] or electrical stimulation on the upper palate [58]. However, realizing both input and output inside the oral cavity has proven elusive, and only a few assistive devices have been demonstrated. Most inspiring to us is the assistive intraoral device by Tang et al. [16], which combines an electrotactile array held by a teeth retainer against the roof of the mouth (for output) with a 9-button keypad (for input) that is operated by the user's tongue. While this device was not usable in everyday tasks, as it is not compatible with eating/speaking (i.e., it is a thick retainer with cables coming out of the mouth), it nonetheless demonstrated the potential of combining electrotactile stimulation of the upper palate with tongue input.

We take inspiration from this concept but turn away from the inside of the mouth and, instead, explore converting the user's lips as both an input and output surface for eyes- and handsfree interactions. While previous lip-based interactive devices are promising, most researchers used the lips as *either* an input [8, 22] or output surface [15, 20, 21, 48, 51, 56, 62]. Instead, we propose closing the tactile input and output loop for lip-based interactions by co-locating the input and output directly at the user's lips. The two principles that we leverage in LipIO are (1) sensitivity of the lips-researchers found that the lips are as sensitive as our fingers [54,59]-we leverage this tactile sensitivity for repurposing the lips as an output surface via electrotactile stimulation; and, (2) dexterity of the tongue -the tongue (and also the lips) is an exceptionally dexterous body part, in many ways comparable to our fingers [1, 2, 57]. With this in mind, we engineered LipIO (Figure 1), an I/O device comprised of two flexible sandwiched electrode arrays: an outwards-facing array for capacitive touch and a lip-facing array for stimulation. Thus, while wearing our device, users can feel the state of a user interface by means of electrotactile stimulation of their lips (Figure 1a), and they can respond by touching the felt locations using their tongue (Figure 1b) or the lower lip for coarser input. Moreover, whenever the user touches their lips to input, they feel co-located tactile feedback at the location they touched. This concept, inspired by tactile-transparent gloves [49, 55] is key to enabling eyes- and hands-free interaction.

We conducted three user studies to inform, understand and improve the accuracy of our technical approach to realizing input and output via the tongue and the lips. Our main finding was that participants were able to perceive output on their lips and subsequently touch the same location with their tongue with an average accuracy of 93%, while wearing a LipIO device with five I/O electrodes and co-located tactile feedback.

To demonstrate practical applications for our concept, we implemented four applications that depict different uses of LipIO in everyday contexts: *outputting* the state of an interface via the lips (i.e., our guitar tuner application), controlling appliances via *input & output* on the lips (i.e., our application that allows a user to control a smart door, or our e-bike application that allows the user to switch between controlling the lights or GPS), and even simple games played entirely on the user's lips (i.e., our whack-a-mole game).

Finally, we also present a discussion highlighting further interactive uses for LipIO that go beyond eyes/hands-free and explore, for instance, LipIO as device for accessibility research, as a haptic interface, or as a supplementary modality.

2 RELATED WORK

While there are several works that realized either eyes- or handsfree, our goal was to explore the extreme case in which *both* of these requirements must be satisfied. As such, we focus on approaches designed specifically to support eyes- *and* hands-free interactions.

2.1 Eyes-free and hands-free I/O devices

Sound-based I/O. Sound is the most common modality to realize *both* eyes *and* hands-free I/O. Sound-based interactions that feature *both* input and output have become common in smartphones and smart speakers [45], which provide micro-interactions for setting timers, playing music, etc. However, while this is useful in many circumstances, it is not applicable to all contexts that users might find themselves in. Specifically, sound-based I/O interferes with external sounds, and is harder to use in public settings [37] or in a multi-party conversation [45, 46]. As such, researchers have turned to alternative I/O approaches, namely leveraging the user's body (e.g., gestures, poses) for I/O.

Touch- & gesture-based I/O. One way that researchers have realized hands- or eyes-free I/O is by leveraging some part of the user's body as the I/O interface, i.e., the user can both feel output and can respond with input through a limb. For instance, Gesture Output [50] explored this by actuating the user's fingers via an actuated smartphone screen; users responded via gestures on the same screen, i.e., symmetric I/O. Similarly, ThroughHand [23] enabled users with visual impairments to play interactive games by delivering tactile output on the palm (via a shape display) while providing touch input on the back of the hand. These devices allow users not only to interact eyes-free but even with a high bandwidth (e.g., Gesture Output offers a full A-Z alphabet). However, these approaches also require the user to hold on to a device. As such, researchers have also engineered wearable forms of this concept. For example, Proprioceptive Interaction [36] leveraged muscle sensing and electrical muscle stimulation to realize information input and output via the same limb. Moreover, MuscleIO [9] and BioSync [40] leveraged simultaneous muscle stimulation and sensing to create notifications or share information across two users. While all these are promising in that they realize eyes-free I/O without the need for sounds, they all require the user's hands to operate, which makes these approaches not hands-free. As such, with hands out of the

equation, some researchers turned to the next limb in the human body that possesses significant dexterity to enable I/O interactions: the mouth.

2.2 Mouth-based interactive devices

The mouth and its many organs, such as the tongue and the lips, have an incredible tactile acuity and dexterity, which makes it a suitable target to realize devices that can handle eyes- & hands-free input and output. While technically most speech-based interfaces could also be considered mouth-based I/O, we specifically focus on research leveraging non-speech mouth/tongue movements.

Input. Taking advantage of the dexterity of the tongue, researchers have explored tongue-based input. One typical approach is to attach a retainer-like device in the oral cavity that senses tongue movements. This includes capacitive touch sensing [16, 30, 32], magnetoresistive sensing [43] and optical sensing [14, 52]. Another approach is to use an external device to measure tongue movements, such as cameras [34, 41], ultrasound imaging [31], magnetic sensing [18, 19], pressure sensing [6], doppler radars [12], or EMG to measure tongue movements [38, 39, 53, 65]. As an alternative technical approach, *ChewIt* [10] uses a chewing gum-like device that is tongue operated.

Output. To take advantage of the high tactile sensitivity of the lips, researchers have explored lip-based output. For example, *LipNotif* delivers tactile notifications to the lips using ultrasound [20, 21]. Similarly, Shen et al. leveraged this approach for VR feedback [56]. While ultrasonic-based lip output allows for precise stimulation, it requires users to carry around large haptic displays comprised of hundreds of small ultrasonic transducers. Alternative lip actuators have also been explored to reproduce realistic virtual sensations such as drinking [15], lip contacts [51], and wind on lips [48, 62]. However, much like ultrasonic arrays, vibration motors, servo motors, or fans used to implement these devices are also large and impossible to be mounted to the user's lips directly.

Mouth-based I/O. Unfortunately, while the combination of gesture-based eyes-free input with eyes-free output has yielded a number of devices (e.g., the aforementioned [9, 23, 36, 40, 50]), the same has not happened to mouth-based devices. In fact, to the best of our knowledge, there is only one mouth-based I/O device [16]. This is a retainer-like device composed of an intra-oral keyboard for the tongue (input) and an intra-oral electrotactile stimulator for the upper palate (output), which enables two-way tactile communication between the system and the user. While this work opened up possibilities for mouth-based I/O interfaces, the device is still thick, placed inside the oral cavity, and connected to an external device via cables, which interferes with tasks such as speaking. Furthermore, it only proposed one notification application that uses only tactile output. In comparison, LipIO advances mouth-based I/O by leveraging a smaller form factor directly on the lips, which is demonstrated by a range of mobile & eyes- & hands-free applications.

2.3 Tactile acuity of the lips & dexterity of the tongue

LipIO builds on the high tactile acuity of the lips as the output surface and the high dexterity of the tongue as the input.

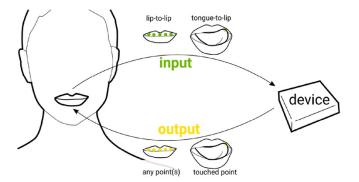


Figure 2: Interaction paradigm in LipIO: lips as input *and* output surface to control a target application.

Lips' tactile sensitivity. Researchers have found that lips are as or more sensitive than fingers in the grating orientation discrimination test [54, 59]. Similarly, lips display a high tactile acuity in electrotactile stimulation [35].

Tongue's dexterity. The tongue has a high tactile sensitivity rivaling that of the fingers [59]. On the motor side, the tongue can form different shapes using ten different muscles [57]. The tongue also displays a relatively fast reaction time of around 600ms [11]. None of this is surprising as the tongue plays essential roles in speaking and eating [2]. In fact, the tongue's brain "real estate" is one of the largest in the primary sensory and motor cortical areas [44].

3 OUR APPROACH: LIPS AS AN INPUT AND OUTPUT SURFACE

Figure 2 depicts the fundamental concept of LipIO: (1) a user controls an external interactive device by using their **lips as an input surface** (via touch input on lips, via tongue or opposite lip); and, conversely, (2) the interactive device responds and informs the user by using their **lips as an output surface** (via electro-tactile stimulation of the lips).

As a result, LipIO implements a new example of symmetric I/O interaction [50], in which users input and output using a very similar vocabulary on the same surface. Moreover, by expanding the notion of symmetric I/O beyond hand gestures and to the lips, our concept enables creating new types of interfaces, especially useful in **eyes- and hands-busy situations**. Yet, this concept does not need to be limited to eyes- or hands-free and can also be used as a supplement to existing modalities (e.g., LipIO + speech I/O, LipIO + gestures, etc.), as an accessibility I/O interface, and so forth.

LipIO widgets. To enable interacting with applications via one's lips, we designed four simple interactive widgets, depicted in Figure 3, which were inspired by those found in the conventional GUI. Note that when the user inputs via any of these widgets, they concurrently receive feedback from LipIO in the form of electro-tactile stimulation at the touched location, which allows users to feel where they are touching. Our four interactive lip widgets are: (1) **momentary push button** is an input widget, created from a single I/O electrode pair, which enables users to trigger actions when its sensing electrode is touched; (2) **smack** is an input widget, akin to

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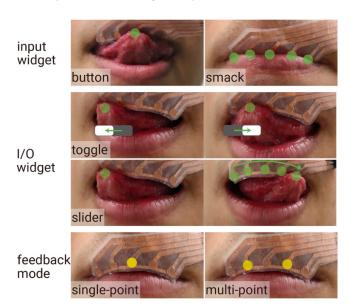


Figure 3: Main interaction components that enable users to interact via their lips in LipIO.

an invocation gesture, created from all I/O electrode pairs, which enables users to activate/deactivate/switch LipIO applications by smacking their lips together (similar to saying "pa" in English); (3) **toggle** is an I/O widget, created from two adjacent I/O electrode pairs, which enables switching between two values (by sliding to the left or right electrode) or reading its state (by touching it, the user can feel which one is active, left or right); and, finally, (4) **slider** is an I/O widget, created from at least three adjacent I/O electrode pairs, which allows the user to input linear values (by sliding the multiple electrodes in to left or right and stopping at the desired level) or read its state (by feeling which electrode is the last in the stimulation sequence).

Feedback modes. Any interactions with LipIO can benefit from two distinct electro-tactile stimulation modes: (1) **single-point feedback**, in which users feel one electrode at a time (e.g., button press, toggle slide, slider swipe)—as we show in our applications, even just a single point of stimulation can yield expressive feedback as the temporal profile can be controlled, e.g., render patterns; and (2) multi-point feedback, in which users feel two or more electrodes being stimulated concurrently (e.g., rendering simple animations on the lips, vibrating all points to confirm a lip-smack gesture, etc.). We achieve this technically by time-based multiplexing (i.e., switching rapidly between electrodes).

Leveraging "classic" touch-based interactions. If needed, LipIO-based applications can also leverage two interactive techniques typically found in touch-based interfaces (depicted in Figure 4): (a) differentiating between short (<0.5s) and long (>2s) presses; and (b) allowing users to touch adjacent targets by touching the upper lip with a wider region of the tongue or with the lower lip.

Dual lip interface. Finally, although we limited all our examples to one single LipIO device on the upper lip (based on findings from our Experiment 1, which revealed this is the most ergonomic touch location for the tongue), specialized applications can even use both

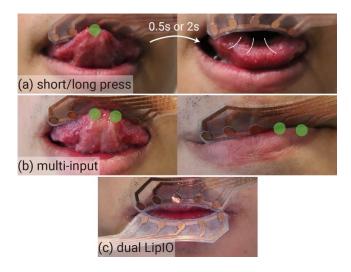


Figure 4: Additional interactive techniques added to LipIO: (a) short vs. long press; (b) allowing touching adjacent targets by touching the upper lip with a wider region of the tongue or with the lower lip; and (c) using both lips as I/O surfaces.

lips as I/O surfaces by wearing two of our devices, which increases I/O to 10 points.

4 CONTRIBUTION, BENEFITS, AND LIMITATIONS

Our key contribution is that we propose, engineer, and evaluate a new I/O device that enables lip-based interfaces. It also provides a new technical approach to realizing eyes-free and hands-free I/O, especially for micro-interactions.

Our system has four benefits: (1) it provides eyes- and hands-free interface; (2) it is flexible and fits the curve of the lip; (3) it features co-located tactile feedback, leading to a usable I/O accuracy (93%); and (4) our device does not drastically interfere with everyday tasks such as speaking and eating.

Our system is limited in that: (1) as any electrotactile device, it requires calibration (~5 minutes); (2) it sometimes requires recalibrating capacitive sensors due to saliva, though this takes only a couple of seconds; (3) it interferes with some lip-interactions, such as adding lipstick or lip balms; and (4) it requires the user to attach a device to a very visible location. As for the latter, Chen et al. showed the social acceptability of mouth microgestures including "slide tongue along top lip," a key interaction of LipIO, was rated 5.42 out of 7 [5], which suggests our interaction can be already socially acceptable. Also, one can even adopt transparent electrotactile actuators for inconspicuous LipIO in the future [25].

5 APPLICATIONS

To illustrate this novel concept, we implemented four applications: (1) an interface to unlock a smart door; (2) a guitar tuner; (3) an e-bike interface; and (4) a lip-based "whack-a-mole" game. These four applications represent examples of applying LipIO to everyday situations in which users might find their eyes and hands occupied with primary tasks but simultaneously desire to control an interface.

5.1 UI metaphors on the lip: unlocking a smart door while eyes- & hands-busy

In this example, we depict how LipIO's tactile stimulation allows for rendering simple animations that create useful interface metaphors. Here, we depict a user who is listening to music while cleaningtheir hands, ears, and eyes are occupied with these primary tasks. Figure 5 depicts the whole interaction: (a) a visitor rings the door; (b) LipIO renders the "ringing" via its tactile feedback (vibration at 3 Hz) at the center electrode-this vibration is a typical UI metaphor for ringing; (c) in response, the user touches the ringing electrode to (d) stop the bell ringing. Now, to open the door, (e) the user swipes from left to right-a typical UI metaphor for sliding a door open. Now, LipIO renders the state of the door, so the user feels as their friend walks in: $(g \rightarrow i)$ the stimulation fans out from the center electrodes every 700ms-a metaphor for opening; and then, as their friend closes the door, $(j \rightarrow l)$ the opposite animation is rendered to the electrodes. Finally, (m) locks the door by repeating the swipe gesture in the opposite direction of their initial unlock.

5.2 Taking advantage of lip-based tactile output: a hands-free & eyes-free guitar tuner

Our second application demonstrates how LipIO takes advantage of its electro-tactile output of the user's lips to enable new types of hands- & eyes-free interactions. In this case, our user is tuning their guitar while freely moving on stage and keeping eye contact with the audience-something not possible with existing tuners which require eye contact. Our LipIO tuner borrows directly from typical tuners, which depict visually in which direction the string's frequency deviates from the expected note (up, down, or tuned)-our implementation follows this layout to leverage familiarity. Figure 6 depicts this interaction: (a) the user plays while looking at the audience; the user invokes the tuner using the lip-smack: (b) to do this, they join their lips together and feel co-located tactile feedback to confirm this gesture started. Then, they (c) smack the lips (as if saying the sound "pa"); (d) now, as the user tunes the string with their hands, (e) LipIO stimulates the leftmost point in response, indicating this string is out of tune, too low; then, (f) LipIO responds by indicating that the string is now slightly overpitched, which the user corrects by lowering; (g) finally, LipIO indicates that the string is tuned; (h) the user repeats the lip-smack gesture to (i) dismiss LipIO.

5.3 Multi-page interface: switching between two applications in an e-bike

While we limited our array to five channels to ensure an I/O accuracy of over 90% (see our three *User Studies*), some microinteractions might still require more than five options. One way to implement these is by adopting a multi-page layout. To demonstrate this, in our third application, we depict how a toggle interface switches between two UI pages, each features different UI elements of the user's e-bike: a GPS navigation page and a gear settings page. Figure 7 depicts the interaction: (a) the user is biking while wearing LipIO; (b) the selected UI page is the GPS, informing the user to keep moving forward, which they feel by means of the stimulating electrode (the center of the three navigation electrodes). Then, (c)

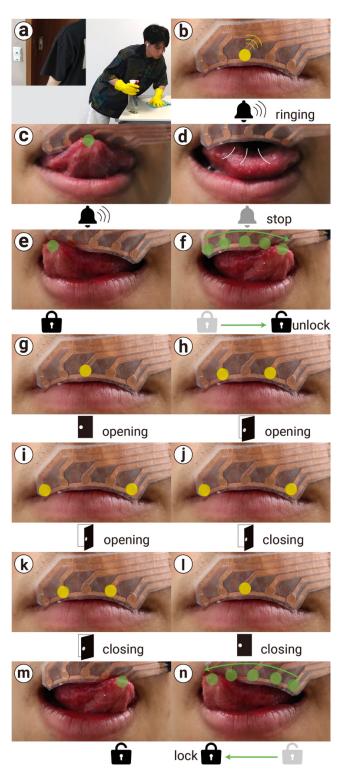


Figure 5: Leveraging animations on lip-based output & input surfaces, LipIO can use metaphors to represent the state of the interactive device. Here, we use these metaphors to represent a doorbell, opening/closing of a door, and lock/unlock of a door.

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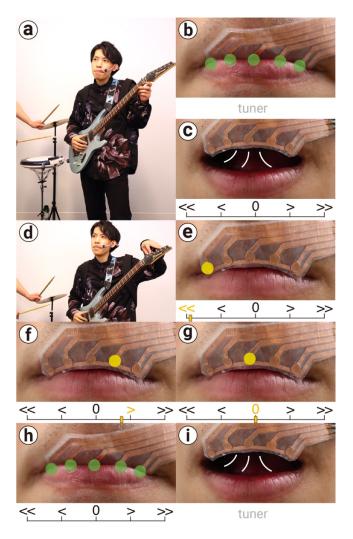


Figure 6: Interacting with a guitar tuner solely via LipIO.

the user switches to the gear application by touching and "flipping" the toggle with their tongue; (d) now, in the gears page, they feel that their e-bike is in the lowest setting (least motor assistance); the user adjusts the gear by (e) touching the current gear and (f) sliding the tongue to the next gear; until, (g) the e-bike is now the highest gear (maximum motor assistance). Finally, (h) they switch to the GPS page, and (j) they feel the GPS indicating a left turn.

5.4 Lip-based game interface: playing "whack-a-mole" game

Our fourth application is, conceptually speaking, the most unique as it utilizes the lips as I/O surfaces to render a gaming experience, which to the best of our knowledge, has not been explored (the closest analog to this are proprioceptive-body games using hand gestures [4, 36]). Most game UIs require users to focus their eyes, ears, and hands on the game screen. Instead, in this application our user is playing a "whack-a-mole" game while searching for their friend and holding luggage (i.e., their eyes and hands are busy).

a) (\mathbf{b}) gps gear indicate forward C **(d**) gps gear gps gear 2 3 2 shift to gear mode gear = 1 (\mathbf{f}) **e**) gps gear gps gear 2 3 2 shifting gear **(g)** (\mathbf{h}) gps gear gps gear 3 2 \leftarrow gear = 3 shift to gps mode (j) gps gear

Figure 7: LipIO toggle to switch between two application pages: a GPS application and a gear shift application.

indicate left

Figure 8 depicts the entire gameplay: (a) the user is waiting for a friend, holding an umbrella and luggage; (b, c) the user starts the "whack-a-mole" game using the lip-smack gesture; (d) the mole is moving between electrodes at random time intervals and in random order. The mole is in the second hole; (e) the mole escapes to the first hole; (f) if the user can "whack" the mole with their tongue before it moves, they receive three consecutive feedback, indicating success; (g) the mole escapes to the fourth hole; (h) if the user taps an empty hole, nothing happens; (i) the user can dismiss the game by repeating the lip-smack gesture, and (j) the game is dismissed.

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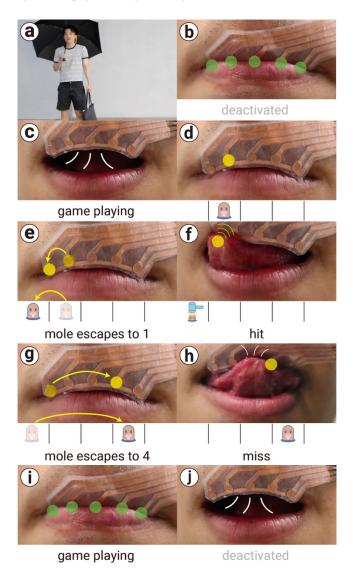


Figure 8: A "whack-a-mole" game played solely via LipIO.¹

6 IMPLEMENTATION

To help readers replicate our design, we provide the necessary details. To accelerate replication, we provide all the firmware and schematics of our implementation². LipIO is comprised of three key components: (1) a flexible sensing electrode array, (2) a flexible electrotactile actuation electrode array, and (3) its electronic circuitry.

6.1 Flexible electrode array for lips

Printing electrode arrays. Since our user studies (Study#2 and Study#3) provided participants with their own electrode arrays for the sake of hygiene and COVID protocol, we sped up the fabrication time of these using conductive inkjet printing, which was

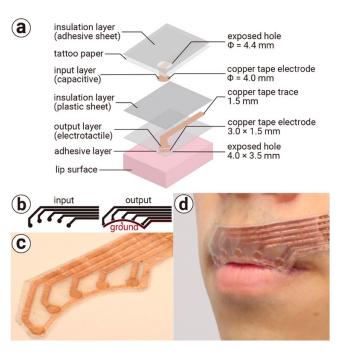


Figure 9: Detail of electrode layers used to realize LipIO.

achieved using a commodity inkjet printer (EPSON PX-S160T) that printed a silver nanoparticle-based ink (Mitsubishi NBSIJ-MU01) on a white opaque coated paper (Mitsubishi NB-RC-3GR120)—inspired by *Tactlets* [13]. Instead, to achieve our final form factor, which is partially transparent, we cut copper tape (LOVIMAG) using a craft cutter (Cricut Explore Air 2)—inspired by *DuoSkin* [28]. We chose this approach because we found our copper tape results to last longer than our screen-printing results (similar to [61, 63]), and we especially found it more robust to bending. This approach takes a bit longer than conductive inkjet printing but is better for visual clarity. Each electrode array is taped to a flexible flat cable via z-axis conductive tape (3M) and connected to the electrical circuit. We measured an end-to-end resistance of ~0.5 Ω from electrodes to each of their path ends.

Stacking electrode arrays. Our two electrode arrays are stacked together, as depicted in Figure 9. To prevent the output layer and the lip surface from affecting the capacitive sensors, we inserted an isolating layer of plastic sheet $(135\mu m)$ between the input layer and the output layer. We placed a temporary tattoo paper (Silhouette) over the sensor to prevent the tongue from directly touching the sensor and further placed a laser-cut adhesive sheet (Silhouette, $140\mu m$) on top of that to insulate the non-electrode parts from the tongue and thus block incorrect touch recognition. Figure 9 (b) shows the path design for the input and output electrode array. Figure 9 (c) shows the whole device. The resulting stacked and co-located array is $360\mu m$ thin and flexible to fit the curve of the user's mouth, as depicted in Figure 9 (d).

Attaching to the lips. Finally, to attach the electrodes to the user, we add another laser-cut adhesive sheet under the output layer. We peeled off the protective sheet right before attaching the device to the lips, leaving only the adhesive. After using the device, the

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¹This figure was designed using an image from Flaticon.com

²https://lab.plopes.org/#LipIO

adhesive strength can be restored by re-applying another adhesive sheet of the same shape.

Limitations. There are always trade-offs to consider when fabricating thin conductive-based devices. For instance, decreasing electrode radius beyond what is shown can result in decreased conductivity and subsequently decreased sensor/actuator response. Similarly, while we also explored thinner trace widths, this also resulted in decreased conductivity. As such, after considering these trade-offs, we settled on a 4 mm electrode—this allows for a maximum of ~9 electrodes in one LipIO device.

6.2 Electronics & circuit design

Sensing. To realize our capacitive sensing, we integrated an NXP MPR121 (on-chip capacitive touch controller with 12 independent channels), which we chose due to its high-dynamic range (measures changes in electrode capacitance ranging from 1 pF to 2000 pF)—since capacitive sensing on the lips was a novel technical territory, this afforded the highest dynamic range to ensure we can detect different types of touches, such as lip-to-lip or tongue-to-lip. Moreover, the MPR121 provides an onboard hysteresis filter and dynamic baseline calibration, which allows us to minimize any false positives caused by residual saliva left after tongue touches.

Actuation. For electro-tactile stimulation, our system feeds off an external electrical stimulator. For our studies, we utilized the medical-compliant Hasomed RehaStim as the source of electrical stimulation, but any other stimulator is interchangeable, such as smaller devices including *Biosync* wearable stimulator [40] or [3, 27]. To control which electrode outputs the stimulation, we implemented an array of Sharp PC817XxNSZ1B photo-relays arranged in a 1:N multiplexer configuration. These photo-relays are rated for up to 80V at 50mA of current, which is 10x above the typical current values for tactile stimulation; in fact, in our studies, we utilized only 0.5mA-10mA (adjusted to the participants' comfort). Moreover, our channel multiplexer affords a response time of 4μ s, enabling us to switch between channels or even "simultaneously" stimulating multiple channels by means of time-multiplexing.

6.3 Application-specific implementations

Guitar tuner was implemented with Pure Data and runs on a laptop that communicates to LipIO via USB. It tracks the current note using an FFT (window of 2048 samples at 44.1kHz). The fundamental frequency is extracted and compared to known guitar string notes. If the difference between the fundamental and the target note is larger than one half-note away, LipIO stimulates electrodes #1 or #5 (depending on whether it is above or below the target); similarly, below one half-step, it will stimulate #2 or #4 respectively; finally, if the note is less than a quartertone to target, it stimulates #3.

Bike application & Door application were implemented using Processing and run on a laptop that manages the wireless communication. Moreover, for the bike application, this Processing application communicates to the Android phone (Wi-Fi), LipIO (USB), and to the e-bike interface, which we controlled using 5V relays and an Arduino (USB).

Whack-a-mole game was implemented as a self-contained application directly in the microcontroller that runs LipIO. We added two game designs specific to LipIO. First, considering that the reaction time of the tongue is around 600ms [11], we set the time interval of the mole's movement randomly between 800ms and 1500ms. Second, imitating the usual whack-a-mole game, this app recognizes an input when the tongue is *pressed* to the lips, in contrast to the other applications that detect input when the tongue is *released* from the lips.

7 USER STUDIES

Overview. We conducted three user studies to inform, understand and improve the accuracy of our concept of using the lips as input and output surfaces. (1) In our first study, we assessed which of the lips is easier to touch with one's tongue; we found that, in about 90.0% of the trials, participants found the upper lip was easier to touch with their tongue-this allowed us to understand that the upper lip was, ergonomically, the best target for our investigations, which we used in our subsequent studies. (2) In our second study, participants felt electrotactile stimuli in their lips and attempted to touch the felt position with their tongue-this task was purposefully performed with no-tactile feedback and eyesfree, which is relatively difficult as participants could only rely on tongue proprioception and vague lip tactile feedback during tongue touch. This was a necessary step because before enabling the real-time and co-located tactile feedback (i.e., to feel where the system senses the tongue touches), we needed to understand the basics of tongue-to-lip interactive touches, to which there was no prior work. The raw data of participants' touches were used to assess which common touch sensing approach (maximum-value or centroid) was most suited for tongue-to-lip touches. We found that a centroid-based approach was better at estimating where the tongue was touching on the lip. We then implemented and integrated this centroid-sensing method in our device to enable users to feel co-located output at the position they are currently touching. Finally, (3) in our third study, we investigated the trade-offs and benefits of our implementation, namely: number of electrodes and co-located feedback. We found that adding the co-located feedback improved the participants' accuracy from an initial average of 41.3% (without co-located feedback) to an accuracy of around 66.3%. Finally, we found that reducing the number of I/O electrodes from 9 to 5 further improved the participants' average accuracy from 66.3% to an accuracy of 93.1%, which we deemed usable for building our applications.

All our user studies were approved by our Institutional Review Board (IRB21-1229).

7.1 Study#1: which lip is easier to touch with the tongue?

Study objective. Prior to designing any of our devices, we conducted a preliminary study to assess which of the lips is easier to reach with one's tongue—this determined a critical factor, i.e., which lip is more suitable for tongue touches, which informed our subsequent design decisions, implementations, studies #2 & #3 and applications.

Participants & apparatus. We recruited 8 participants without any motor impairments on the lips or tongue (M = 24.6 years old, SD = 2.6; three identified as female and five as male). We applied

five equally spaced 2mm x 2mm tape squares on the participants' upper and lower lips (spacing was relative to each participant's lip length).

Trial design & procedure. Participants were asked to touch a pair of positions (upper vs. lower) with their tongue (no mirrors, task was performed eyes-free) and chose which, upper vs. lower lip, was easiest to touch. Each participant conducted 15 trials (5 pairs \times 3 repetitions) in a randomized order for a total of trials across all participants.

Results. We found that most trials reported that the upper lip was easier to touch (average of 90.0%; SD = 9.4). This is in line with the ergonomics of the tongue since the protrusion movement of the tongue outside of the oral cavity is minimal if the tongue touches the upper lip. Conversely, the protrusion is longer and more demanding for touching the lower lip. While this motivated our decision to study LipIO on the upper lip, none of our participants voiced discomfort or inability to touch the lower lip, which can enable future versions of LipIO-type devices on both upper and lower lip.

7.2 Study#2: understanding tongue-to-lip touch (without tactile feedback)

Study objective. Since there is no prior work in tongue-to-lip touches and to develop a real-time interactive system that uses capacitive touch to detect tongue-to-lip touches, we first gathered participants' tongue touches on different lip targets. The goal of this study was to understand how the user touches the lips with their tongue in an eyes-free manner and to devise methods to achieve high accuracy of tongue touch. Note that this task was purposefully performed with *no-tactile feedback* and eyes-free, which is relatively difficult as participants could only rely on tongue proprioception and vague lip tactile feedback during tongue touch.

Apparatus. Participants wore our LipIO device while sitting down, with their head supported by a chinrest—this ensured that the data collection was robust. A keypad was placed near the participants' dominant hand to confirm their input. As previously described, we used 9 electrodes for this study, which is the maximum number of electrodes that we can robustly fabricate in our array, with 4 mm circular electrodes, 4.7 mm apart (see *Implementation* for details).

Trial design. In a single trial, participants felt tactile stimulation in one of the nine locations. Then, they were asked to, eyes-free (no mirrors in sight), touch the point they felt with their tongue (in any way they preferred) and press a button to confirm the location. Once they pressed this button, our apparatus recorded a photograph of their face (with their tongue sticking out at their chosen touch location) and recorded the capacitive sensor values for all the sensing electrodes obtained from the touch sensor controller.

Study procedure. Participants performed 36 trials (9 points x 4 repetitions). Locations were presented in randomized order. This totaled 288 trials across all participants (each trial is comprised of 9 data points from the touch sensors and one image of the participant's tongue touching the sensor array, for a total of 2592 touch values and 288 images).

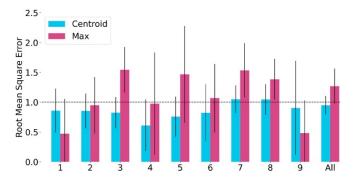


Figure 10: Comparison of the root mean square error between centroid estimator and maximum estimator.

Calibration. Prior to the start of the trials, the intensity of the electro-tactile stimulation was calibrated for all nine points to ensure pain-free operation. The intensity ranged from a minimum of 0.5mA up to the value that the participant deemed clearly noticeable and comfortable, which is the typical calibration threshold from electro-tactile study designs (e.g., [26] or [24]). Moreover, sub-mA adjustments were also conducted, when necessary, by adjusting the stimulation pulse-width from 50 μ s up to 300 μ s (in steps of 50 μ s). After calibration, we registered an average intensity of 2.3mA (SD= 0.9mA; median = 2 mA) with a pulse-width of 223 μ s (SD = 73 μ s; median = 200 μ s).

Lip images. We used a 1080p camera that gathered images of participants' lips with their consent. Our camera feed was corrected for distortions via a fisheye lens calibration software using a printed checkerboard pattern.

Participants. We recruited eight new participants (M = 22.9 years old, SD = 2.2; five identified as male, three as female). Participants were compensated 30 USD and consented to the photographing of their faces.

Results. Figure 10 depicts our main findings by measuring the root mean square error (RMSE) for two possible touch estimators: in **pink**, a maximum-value estimator (i.e., an estimator that outputs as the touched location the highest value sensor reported from all the electrodes) and in **blue**, a centroid estimator (i.e., an estimator that outputs as the touched location the centroid of all the sensor values). We found that the error was lower for the **centroid estimator** (M = 0.95; SD = 0.15) when compared to the **maximum estimator** (M = 1.27; SD = 0.29). These error values were calculated using the electrode index (1-9). To exemplify, a value of "1.0" means that the stimulating electrode and the touched electrode are off by one electroide. Our results suggested that, similar to early touchscreens, a centroid-based approach performed better than maximum-value for tongue-to-lip touches.

The photographs taken from participants' lips provided some additional evidence that the maximum-value estimator led to more error than the centroid estimator. Figure 11 depicts examples (one per participant) in which the correct target (annotated in **blue**) was aimed for. In these examples, it appears that the tip of the tongue (annotated in **pink**) was the closest anatomical feature to the target electrode. However, while the tip is touching the target electrode, the surrounding tongue areas are *also* touching adjacent



Figure 11: Exemplary trials of participants touching suggest that participants might aim with the tip of the tongue (photos with participants' consent; all participants depicted).

electrodes—this happens because our tongue is wider than the electrodes (similar to the well-known "fat finger" problem [60]). This is where the centroid estimator outperforms the maximum-value estimator: since the tongue lands fairly symmetrical during lip touches, the tip tends to be found closest to the center of the raw touch data, which the centroid estimates better.

Discussion. We found the RMSE to be around an average of 0.95 (SD = 0.15), which suggests participants tended to be off by about one target in these trials-again, we remind the reader that this was purposefully a difficult task as participants received no tactilefeedback while targeting, i.e., they could only judge the location they were touching based on tongue proprioception and vague tactile feedback (as the tongue presses on the flexible tactile array, the touch pressure is not focal but blurred over the *whole* array). This is precisely what we will address by adding our co-located tactile feedback that renders which point the user's tongue is currently touching. Yet, before we could enable this real-time tactile feedback, we needed to collect raw data of participants' touches to understand what sensing approach to use, which as aforementioned was found to be the centroid. Moreover, in these extreme trials (eyes-free and almost tactile-free), we measured, on average, low accuracy of 41.3% (SD=7.7), which allows us to advance two possible strategies to improve the accuracy in our subsequent study: (1) adding the co-located tactile feedback to indicate which location the tongue is currently touching; and, since the RMSE suggests that participants tended to be off by one target, (2) reducing the number of available I/O locations by skipping every second location, i.e., decreasing from 9 points to 5 points.

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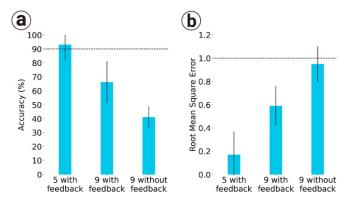


Figure 12: Comparison of the performance of the three methods (a) by accuracy (b) by root mean square error.

7.3 Study#3: measuring & improving the accuracy of real-time LipIO touches

Study Objective. Now, armed with our centroid-based estimator, we could measure the performance of LipIO in real-time. Now we could provide co-located tactile feedback anytime the lips were touched. This study was designed to allow us to understand the impact of our two aforementioned strategies to improve the accuracy found in Study 2: (1) what is the impact in accuracy provided by the co-located tactile feedback? and (2) what is the impact in accuracy provided by reducing 9 touch locations to 5 touch locations?

Apparatus. We utilized the same apparatus as in our previous study, except this time participants received co-located tactile feedback. This feedback was determined in real-time using the previously validated centroid estimator.

Trial design. We followed the same trial design from our Study 2 (i.e., participants felt a tactile stimulation in one of the possible locations and were asked to touch the point they felt with their tongue, confirming it with a button press).

Conditions. We used our 9-point electrode array from Study 2 and an additional 5-point electrode array to investigate the impact of the reduction of touch points.

Study procedure & calibration. We followed the same procedure & calibration from Study 2. After calibration, we registered an average intensity of 3.1mA (SD = 1.8mA; median = 2 mA) with a pulse-width of $145\mu s$ (SD = $92\mu s$; median = $100\mu s$). These calibration values were similar to those of Study 2, with the median intensity at the exact same level and the median pulse-width $100\mu s$ lower—this suggests that individual calibrations were consistent.

Participants. To directly compare the improvement over the baseline recorded in the previous study, we re-invited the same participants from Study 2, and they were additionally compensated with 30 USD for their participation.

Results. 12 depicts our main findings: First, we found an accuracy of 66.3% (SD = 14.9) when using touch feedback with the 9-point array, as depicted in 12 (a). Compared to the baseline of the previous study (41.3%), in which participants did not receive any tactile feedback, this suggests that touch feedback increased the performance by 25.0%. Moreover, as depicted in 12 (b), the RMSE also decreased from 0.95 (SD = 0.15) to 0.59 (SD = 0.17); yet, this

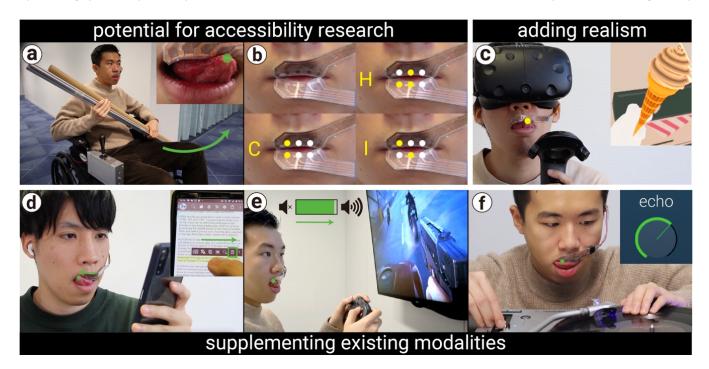


Figure 13: Three distinct types of envisioned practical applications for LipIO that go beyond eyes- and hands-free interactions.

is still comparatively high, which still suggests that participants often are one electrode away from the target. As such, we turn to analyze our 5-point array. We found that the RMSE also decreased from 0.59 to 0.17 (SD = 0.20). More importantly, we found that the reduction of electrodes further increased the performance by 26.8%, **resulting in a final average accuracy of 93.1%** (SD = 11.2).

7.4 Study conclusions

Taken together, our results suggest that we reached an accuracy of around 93% for our most important touch-based interactions with LipIO, i.e., tongue-to-lip touches. Moreover, we observed that adding the co-located tactile feedback is important for this type of device, as it increased the accuracy by ~25%. Our results are particularly exciting in that our participants had **no training in using LipIO**, except for a few calibration trials to adjust the intensity of the electrotactile sensations—as such, we can safely envision that given additional hours of using this device, a prospective user could perform even better and might not need the reduction from 9 to 5 electrodes—potentially other spacings and compromises can be explored by researchers building on our findings. Regardless, we believe that 93% for untrained individuals provided validation to enable us to explore a range of applications with our device.

8 FURTHER PRACTICAL APPLICATIONS

While we implemented four applications that demonstrated how LipIO supports interactions while the user's eyes & hands are occupied with other main tasks, we believe that these represent only one of many interactive domains for LipIO. In this section, we envision how future researchers might apply our concept to further practical applications, which we depict in Figure 13. In particular, we highlight three use cases that go beyond eyesand hands-free interactions: (1) LipIO as a potential device for accessibility research, (2) LipIO for enhancing realism; and (3) LipIO as a supplementary modality.

1. Potential for accessibility. Like many other aforementioned tongue/oral interfaces [17, 18, 29], LipIO might be applied to the research in accessibility. In this domain, LipIO presents two promising advantages: (1) Unlike existing intraoral interfaces, which typically require attaching magnetic trackers to the tip of the tongue (typically via adhesives or piercings), LipIO is applied using skin-safe adhesives that are simpler to attach/remove. (2) The vast majority of the prior work on tongue/oral interfaces for accessibility is limited to input-only; instead, LipIO presents users with an input surface that can also render collocated output. We depict an envisionment of this in Figure 13 (a), in which a user controls their motorized wheelchair via LipIO. Furthermore, tactile encoding of information is also possible. Figure 13 (b) depicts how LipIO can be extended, for instance, to render braille to lips-this is inspired by [33, 42, 66], but, instead, depicts how users might be able to read braille via their lips with LipIO. With regards to these envisioned applications, it is important to note that LipIO will not, by itself, solve any inherent challenge faced by users with disabilities, not only because it is an emergent interface that has not been yet explored in the accessible domain, but, more importantly, because no technological solution should "just solve" the unique experience of these individuals. Rather, we are inspired by the potential uses that LipIO might have in accessibility research.

2. Adding realism to lip-based interactions. A different use for LipIO is as a haptic interface to increase the realism of virtual interactions. For instance, Figure 13 (c) depicts an envisioned use of

LipIO to render a more realistic sense of tasting virtual ice cream this is inspired by prior work that applied electrical stimulation of the tongue to render virtual basic tastes (e.g., sour, salty, bitter, and sweet sensations as in [47]). While the existing methods to deliver these tongue stimulations require cumbersome electrodes directly clipped to the tongue (e.g., [47]), LipIO can leverage its vantage point to stimulate the tongue by momentarily switching the sensor, via a multiplexer, to act as another electrotactile actuator whenever the user licks the sensor.

3. Supplementing existing modalities. Finally, LipIO can also work as a *supplementary* modality that enriches an existing interaction. For instance, Figure 13 (d) envisions LipIO as a supplementary modality for interacting with a touchscreen; in this interaction, sliding the tongue controls the contextual pop-up menu of options to the user's currently touched location. Similarly, Figure 13 (e) envisions LipIO as a supplementary modality to control the volume of this videogame experience without the need to invoke sub-menus or use a remote controller. Finally, Figure 13 (f) depicts a different usage of LipIO as an additional input for a DJ application—a situation in which users always need more inputs since they are typically undertaking several simultaneous tasks. In this envisioned example, the DJ uses LipIO to control the amount of "echo" while simultaneously adjusting the tempo of a secondary song they are about to mix in.

9 FUTURE WORK

Finally, we highlight how future researchers might extend LipIO by (1) expanding its fabrication or via (2) further studies.

Further exploration of device fabrication. It is possible to expand LipIO by using fabrication techniques that might reduce the hardware footprint. One such technique is to switch to substrates that allow for thinner printed electrodes (e.g., [63]). Another approach is to reduce the device to a single layer and temporally multiplex the electrodes as either inputs or outputs (e.g., [40]). Moreover, it is possible to explore directly applying conductive paint to the skin (e.g., [7]). Finally, further size reduction is possible by fabricating a customized printed circuit board with a wireless unit.

Future studies. As the first step in this territory of closed-loop lip interactions, our work focused on proposing, engineering, and evaluating the technical feasibility to facilitate future research. Once the device fabrication of devices inspired by LipIO matures, further research is required to evaluate the usability of future versions (e.g., their comfort or cognitive load during use [5]) or even to evaluate social aspects, such as the social acceptability of future instantiations.

10 CONCLUSION

We proposed, engineered, and evaluated LipIO—a novel eyes- & hands-free interactive device that enables the user's lips to be used simultaneously as an *input and output surface*. LipIO is built by stacking two flexible electrode arrays: an outwards-facing array for capacitive touch and a lip-facing array for stimulation. Thus, while wearing LipIO, users can feel the state of a user interface by means of electrotactile stimulation of their lips, and they can respond by also touching their lips using their tongue (or also lips for coarser input). Moreover, to facilitate interactions, whenever the user touches their

lips to input, they feel co-located tactile feedback at the location they touched. Using LipIO, we demonstrated a range of eyes- and hands-free micro-interactions, in which users leverage their lips and tongue to, for instance, unlock a smart door while cleaning, tune a guitar while freely moving on stage, switch between two applications in their e-bike, or play whack-a-mole while holding luggage with both hands.

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