Palatal Electrotactile Display Outperforms Visual Display in Tongue Motor Learning

Bing Jiang, *Student Member, IEEE*, Jeonghee Kim, *Member, IEEE*, and Hangue Park, *Member, IEEE*

***Abstract*— Incomplete tongue motor control is a common yet challenging issue among individuals with neurotraumas and neurological disorders. In development of the training protocols, multiple sensory modalities including visual, auditory, and tactile feedback have been employed. However, the effectiveness of each sensory modality in tongue motor learning is still in question. The objective of this study was to test the effectiveness of visual and electrotactile assistance on tongue motor learning, respectively. Eight healthy subjects performed the tongue pointing task, in which they were visually instructed to touch the target on the palate by their tongue tip as accurately as possible. Each subject wore a custom-made dental retainer with 12 electrodes distributed over the palatal area. For visual training, 3 $\times$ 4 LED array on the computer screen, corresponding to the electrode layout, was turned on with different colors according to the tongue contact. For electrotactile training, electrical stimulation was applied to the tongue with frequencies depending on the distance between the tongue contact and the target, along with a small protrusion on the retainer as an indicator of the target. One baseline session, one training session, and three post-training sessions were conducted over four-day duration. Experimental result showed that the error was decreased after both visual and electrotactile trainings, from 3.56 $\pm$ 0.11 (Mean $\pm$ STE) to 1.27 $\pm$ 0.16, and from 3.97 $\pm$ 0.11 to 0.53 $\pm$ 0.19, respectively. The result also showed that electrotactile training leads to stronger retention than visual training, as the improvement was retained as 62.68 $\pm$ 1.81% after electrotactile training and 36.59 $\pm$ 2.24% after visual training, at 3-day post training.**

***Index Terms*— Electrotactile feedback, motor learning, tongue, electrical stimulation, intraoral device.**

I. Introduction

TONGUE has direct motor pathway from the brain and is composed of dexterous and strong muscle fibers, which supports its versatile functions in daily oral activities including swallowing, respiration, and articulation. In the oral phase of swallowing, tongue is controlled in a sophisticated way for harmonious coordination with the masseter muscle activity (*i.e.,* mastication), for food distribution and bolus formation [1], [2]. Contraction of genioglossus muscle of the tongue secures air passage, which is especially important during sleep to resist the gravity and posterior tongue movement at snoring. Tongue also plays an important role in speech, as it shapes the air flow for articulation.

Unfortunately, there are multiple causes that's limiting the tongue control capability, such as spinal cord injury (SCI), repetitive strain injury (RSI), severe arthritis, stroke, Parkinson's disease, Alzheimer's disease, and several other central nervous system disorders [3]–[5]. Even for healthy individuals, nervousness and fatigue often result in limited tongue control capability. Considering the importance of the tongue movement in oral activities, limited tongue control capability may lead to serious limitations in accomplishing daily oral activities and lower the quality of life. For instance, it may increase the risk of tongue bite or aggravate burden of the digestive system. It may also cause speech issues with unclear pronunciation like slurring and stuttering [6] and respiration issues like obstructive sleep apnea [7].

Also, limited tongue control capability leads to challenges in issuing user-defined tongue commands of assistive technologies (ATs) for people with quadriplegia [8]–[11]. As the commands are mostly defined by special tongue maneuver to avoid the MIDAS touch problem and the confusion with the daily oral activities [12], these new tongue trajectories require a lot of training. In our prior work with people after SCI, it took six training sessions (total ~15 hours of training) for new users to arrive at a plateau in a learning curve, even though the easiest oral locations were used for user-defined tongue commands [13].

To promote the motor learning of the tongue and overcome the problems and challenges associated with the tongue motor control, a few training methods have been developed and employed with sensory assistance via multiple modalities including visual, auditory, and tactile feedback. Visual/audio instructions have been provided by speech language pathologists or visualization/sonification of the real-time tongue movement has been provided by multimedia tools [14]–[18]. Also, tactile feedback has been provided by handheld tools like Abilex oral motor exerciser and Speech Buddies [19], [20]. However, the effectiveness of each sensory modality in tongue motor learning has not been well investigated and is still in question.

Visual feedback is often chosen as a rule of thumb to promote the motor control ability [21]. However, the efficacy of visual feedback on motor learning is still in question.

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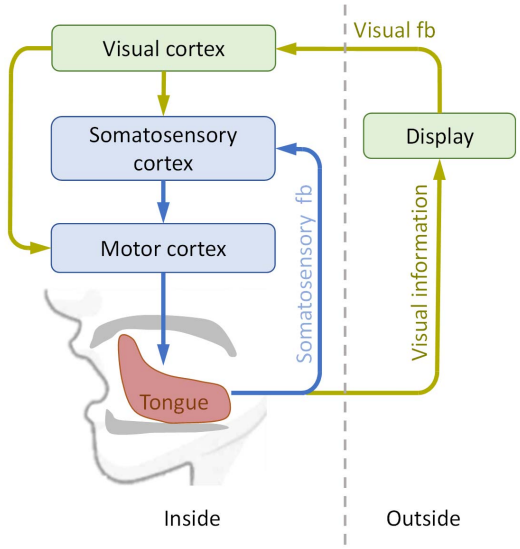


Fig. 1. Tongue learns new maneuvers by tactile and proprioceptive feedback. Providing visualization of the intraoral space helps tongue motor learning, but the complex steps are involved to map the visual information onto the somatosensory cortex. On the other hand, tactile feedback can be directly mapped onto the somatosensory cortex to guide the tongue motor control.

Multiple locomotor studies showed that the lasting effect of locomotor training with visual feedback was minimal, although the motor performance was improved during the training [22], [23]. One study with a task of moving a slide showed the case that visual feedback even inhibited the effectiveness of proprioceptive feedback in motor learning [24]. The complex neural pathway to interpret visual information might be the reason of this questionable efficacy of visual feedback on motor learning. In visuomotor coordination, the human brain is known to process the visual stimuli at multiple levels including the occipital lobe, parietal lobe, and pre-frontal lobe, and generate movement related potential to excite the motor cortex and execute the actual tasks [25]. The mismatch at the visual-proprioceptive conversion may be another reason. For the motor learning with visual feedback, users need to map the visual input to the specific body movement based on proprioception, which involves visual-proprioceptive mapping [26] (see Fig. 1).

The question of visual feedback on motor learning becomes more plausible in the case of tongue motor learning. Tongue motor tasks are not visually guided in its intrinsic form as the tongue is hidden inside the mouth, therefore it is apparent that tongue motor learning happens without visual feedback for most of the cases. Research on spinal neural pathways also showed that visual feedback is more effective for training the limb muscles than the tongue muscles, as limb muscles are controlled via the corticospinal pathway while tongue muscles are controlled via the corticobulbar pathway [27]. One prior study showed that visual feedback does not improve the control accuracy of the tongue muscle, based on the assessment of the repeated tongue-lifting task [28]. Speech studies also showed limited efficacy of visual training. Studies showed that people have limited ability to interpret speech information from visual feedback, with accuracy of only about 50% [29].

Somatosensory feedback might be better suited for tongue motor learning. Somatosensory feedback is critical in any motor learning, as the central nervous system adjusts motor commands by comparing the sensory reference and the actual somatosensory feedback in response to the motor output [30]. Further, somatosensory feedback naturally comes along with tongue movement, while visual feedback engages complex cortical pathway to translate the displayed movement. Therefore, for tongue motor learning, the brain may react to somatosensory feedback faster and more intuitively than visual feedback [31] and neural reorganization (or recalibration) for motor learning may happen more effectively.

Two types of somatosensory feedback are mainly associated with the tongue motor learning - proprioceptive and tactile feedback [32]–[34]. Proprioception is evoked through the stretch and compression of the tongue muscles and tendons during the tongue movement, via muscle-spindle-hypoglossal pathway [35]. However, the neural coding for proprioceptive feedback is complicated [36], and people still didn't find a practically feasible method to augment proprioceptive feedback [37], [38]. Although a few papers reported the proprioceptive modulation by electrical nerve stimulation in the central and peripheral nervous system, the consistency and controllability are limited [39]–[41].

Tactile feedback is evoked at the completion of the tongue movement, when tongue is in contact with the target intraoral location (*e.g.,* hard palate) along with the slight distortion of the tongue surface. Tactile feedback is important in providing the locational information of the tongue relative to the other intraoral environment [30]. Tactile feedback is also important for detecting oral environment. For example, the recognition of food thickness decreases significantly when tactile feedback on palate was removed [33]. For multiple intraoral operations like oral phase of swallowing, pronunciation, and respiration, tongue placement relative to the other intraoral environment is critical. Tactile feedback plays an important role in fine tuning of those intraoral operations, such as tongue control for accurate pronunciation [42]. Further, augmenting tactile feedback is technically feasible with practical approaches available, suggested by multiple studies of electrical stimulation applied via nerve or skin [43], [44].

However, current approaches of providing tactile feedback by handheld intraoral tools (*e.g.,* speech buddies) hinder the natural movement of the tongue. One study assessed the effects of visual and tactile feedback on intraoral sensor position, in the case of typing keypad with an inductive tongue computer interface, and showed that training with visual feedback produced better performance [45]. Yet, the post-experiment questionnaire showed that border structure for tactile feedback impedes tongue movement, which makes the result in question [45].

In this paper, we present a closed-loop visual or electrotactile augmentation system with a wearable intraoral device, and tested the effectiveness of visual or electrotactile assistance on tongue motor learning, respectively. We hypothesize that (1) the tongue motor control ability of pointing target on palatal surface will be improved by visual or electrotactile display providing distance information between the target

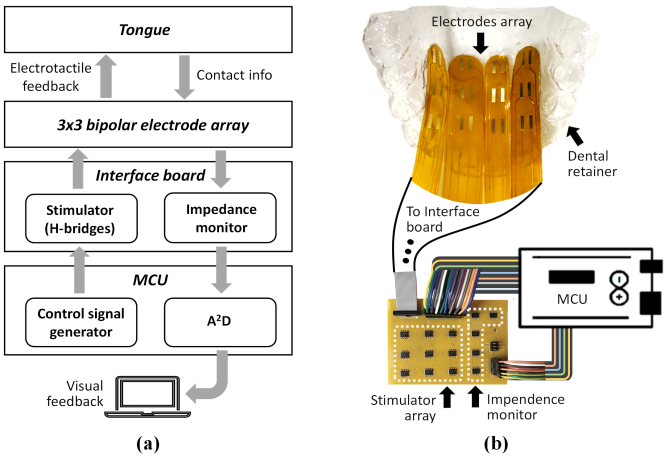


Fig. 2. (a) Operating block diagram of the overall intraoral feedback system. (b) The system consisted of a dental retainer, an interface board with stimulator array and impendence monitor, a MCU, and a computer.

and the contact region; (2) retention of the tongue motor control ability of pointing palatal surface will be higher with electrotactile training than with visual training. This is because visual assistance would engage complex sensorimotor pathways and its effect will be inconsistent at repetition by environmental and cognitive influences; (3) visual training will improve tongue motor control ability in a faster speed than electrotactile training. This is based on the notion that visual feedback delivers larger amount of sensory information in a shorter amount of time, compared to tactile feedback.

Note that, we employed electrotactile feedback instead of vibrotactile feedback for tactile augmentation, because electrotactile feedback can be implemented in the intraoral device with a small form factor and minimal intrusiveness, while vibrotactile feedback needs bulky mechanical structure. Also, electrotactile feedback is free from the mechanical delay and its parameters (*e.g.,* amplitude, frequency) are more controllable than vibrotactile feedback.

II. System Implementation

A. Overall System Preparation for Experiment

A wearable electrical intraoral device was implemented as a minimally intrusive dental retainer. Using an electrode array on a dental retainer, the system not only monitored the tongue contact on the palate but also provided visual or electrotactile feedback to promote the tongue motor learning. Fig. 2a shows the operating block diagram of the system. To provide electrotactile feedback, alternating electrical current was applied to the electrodes via H-bridges controlled by the microcontroller unit (MCU). To provide visual feedback, the impedance change between the electrodes was read by MCU via impedance monitoring circuit. This information of impedance change was also used to monitor the tongue contact during the trials.

B. System-Level Implementation of Visual and Electrotactile Display

For visual display, real-time tongue-palate contact location was displayed on the screen, along with the target location. There was a 3 × 4 LED array on the computer screen corresponding to the electrode layout on the dental retainer. The LEDs were turned off as a default (when there was no contact). Whenever tongue contact was detected, the LEDs corresponding to the contacted electrodes were turned on as visual feedback. The different colors of the LEDs indicated their distance to the target location as shown in Fig. 3 (left).

For electrotactile display, a mild biphasic electrical current pulse was applied to the tongue with specific frequency as the distance information between the target and the tongue-palate contact. As our prior work suggested that subjects feel more comfortable with lower frequency stimulation [46], higher stimulation frequency was used for the electrodes located further away from the target as an error feedback, as shown in Fig. 3 (right side). Further, to provide a clear indicator of the target for electrotactile training, the electrode at the target location was protruded from the surface with about 1-mm height. Note that this protrusion was added only for the electrotactile training, which corresponds to the visual target on the screen provided during the visual training sessions, for fair comparison between visual and electrotactile training.

During the tongue motor training with either visual or electrotactile feedback, one farmost column at one side was deactivated alternately, leaving only three columns (9 electrodes) activated. The order of deactivation was random but balanced between visual and electrotactile trainings (*i.e.,* half of the subjects with leftmost column deactivated for visual training and the other half with rightmost column deactivated for visual training). For each case, the electrode at the center was defined as the "target" location. The electrode array was designed in this way to set the two different target locations and to minimize familiarization, because every subject conducted two sets of experiments with visual or electrotactile feedback (*i.e.,* crossover study). Instructions of "Go" or "Rest" command were provided to subjects by the text displayed on the screen.

C. Hardware Implementation of Visual and Electrotactile Display

The overall electronic system for tongue contact detection and stimulation is shown in Fig. 2b. The system is mainly composed of an interface board, a MCU, and a computer. The electrodes were manufactured on a flexible PCB by immersion gold plating. The protrusion during electrotactile training was added onto the target electrode with lead-free solder (Sterling lead-free solid wire, Harris, OH). The MCU (Atmel SAM3X8E ARM Cortex-M3 CPU, Atmel, CA) read the output voltages of each electrode via a voltage follower (LM2904DR, Texas Instruments, TX) for monitoring the impedance change, and controlled H-bridges (BD6210F-E2, Texas Instrument, TX) for stimulation.

A 3 × 4 electrode array was attached on an Essix-type dental retainer to cover the hard palate (see Fig. 2b). Each bipolar electrode was implemented as a pair of contacts, with 1-mm width each, 4-mm length, and 1.5-mm spacing in between. The first row of the array was adjusted to the line connecting the center of the left and right canine, with

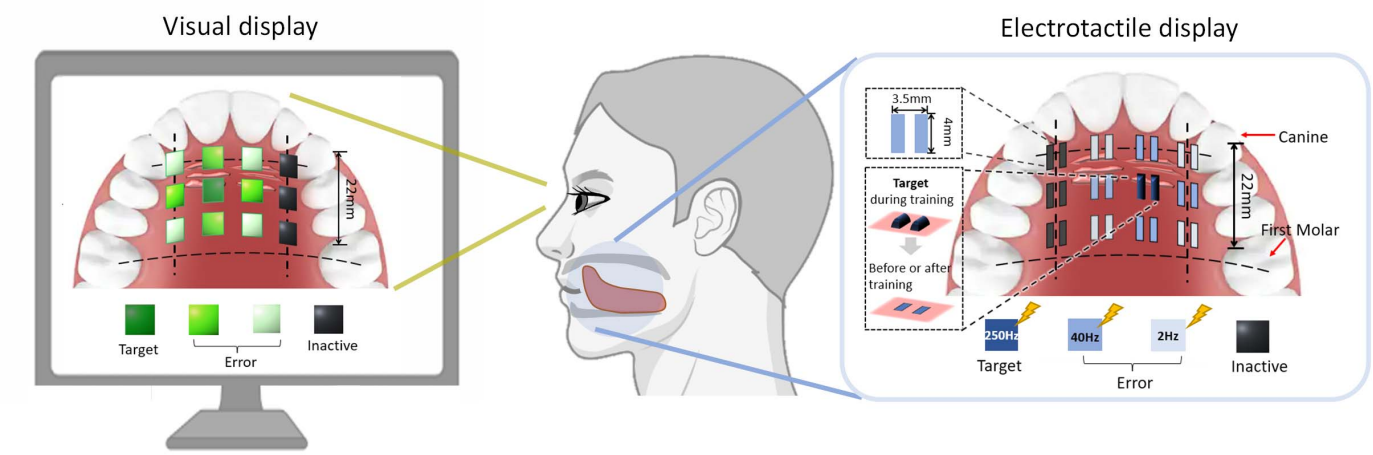


Fig. 3. Overview of the intraoral system with visual and electrotactile display setup. (Left) Visual display: The real-time tongue-palate contact was shown on the computer screen; (Right) Electrotactile display: Stimulation of different frequency was provided to the tongue as electrotactile display.

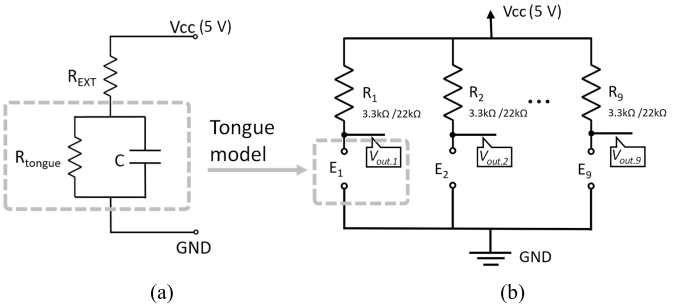


Fig. 4. (a) Equivalent circuit for the training with electrotactile or visual assistance. $V_{out,i}$ ($i = 1, 2, \ldots 9$) are the output voltage of nine electrodes. E_i ($i = 1, 2, \ldots 9$) are nine electrodes in the electrode array. R_i ($i = 1, 2, \ldots 9$) are the external resistor connected to each electrode. When providing electrotactile assistance, $R_i = 3.3$ kΩ, and when providing visual assistance, $R_i = 22$ kΩ; (b) R-C tongue model when contacting the electrode, with external resistors (R_1-R_9).

the four columns evenly arranged as being perpendicular to this line. The leftmost and rightmost columns of the electrode array meet with the line connecting the canines in each side, at the center of the left and right lateral incisor, respectively, as shown in Fig. 3. The four columns were evenly distributed on the hard palate, therefore the horizontal distance between the columns may vary due to the size difference of the hard palate for each individual. The vertical distance between two electrodes in each column were set as 5 mm, to guarantee that the dental retainer not to go beyond the first molar [47] and not to cause any discomfort such as a gag reflex [48].

For electrotactile display, the tongue was modeled as an R-C equivalent circuit as shown in Fig. 4a. When the tongue contacts the electrodes, the resistance of the tongue (R_{tongue}) was 10.28 kΩ on average, while the capacitor would be fully charged within 0.25 ms [39]. After the capacitor was fully charged, the voltage across R_{tongue} can be calculated by (1).

$$V_{out,i} = \frac{R_{tongue}}{R_{tongue} + R_{EXT}} \times 5\ (V) \tag{1}$$

Here, we selected $R_{EXT} = 3.3$ kΩ to make sure that the electrical current can be detected by the tongue without any discomfort. When the tongue was not contacting the electrodes, the biphasic voltage between the two biphasic electrodes changes between $\pm V_{cc}$ (± 5 V). When the tongue contacted the electrodes, the voltage will be divided onto the tongue and the R_{EXT}, and therefore subjects would feel a slight tingling sensation on the tongue as electrotactile feedback. At the same time, the tongue contact can be detected by the decrease in voltage output ($V_{out,i}$).

For visual display during visual training, the stimulation was turned off but the tongue contact was still monitored. The equivalent circuit for monitoring tongue contact is shown in Fig. 4b. Without the tongue contact, R_{tongue} in Eq. 1 will be replaced with the resistance across the H-bridge, the output voltage measured at $V_{out,i}$ was close to V_{cc} (5 V), and would drop when electrodes were contacted by the tongue. To avoid causing any electrical sensation to the tongue during visual feedback, we select $R_{EXT} = 22$ kΩ, and according to Ohm's law, the amount of electrical current applied across the tongue would be approximately 150 μA, which is far below the perception threshold [49] and would not cause any sensation. Meanwhile, according to Eq. 1 and equivalent tongue resistance [49], the voltage measured at $V_{out,i}$ would drop to $\sim$1.6 V when the ith electrode was contacted by the tongue.

D. Threshold Selection for Tongue Contact Detection

To keep the high detection accuracy against the varying impedance of tongue-electrode interface, we selected the threshold for detecting tongue contact close to the voltage without tongue contact, at 90% of V_{cc} (5 V), as shown in Figs. 5a and 5b for electrotactile and visual trainings. The contact was defined only when the voltage at the electrode fell below the voltage threshold for more than a predefined period (500 ms). Accordingly, even in the cases where R_{tongue} was significantly different from the value from the tongue model, tongue contact was detected well. Fig. 5a shows that tongue contact was robustly detected even when the R_{tongue} was $\sim$50 kΩ, which is significantly larger than the resistance in tongue impedance model.

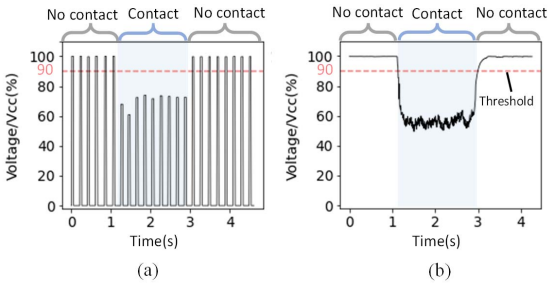


Fig. 5. Exemplary voltage change at one subject when tongue contacted the electrodes. The detection threshold was selected as 90% of the supply voltage, for both the cases of (a) electrotactile training and (b) visual training.

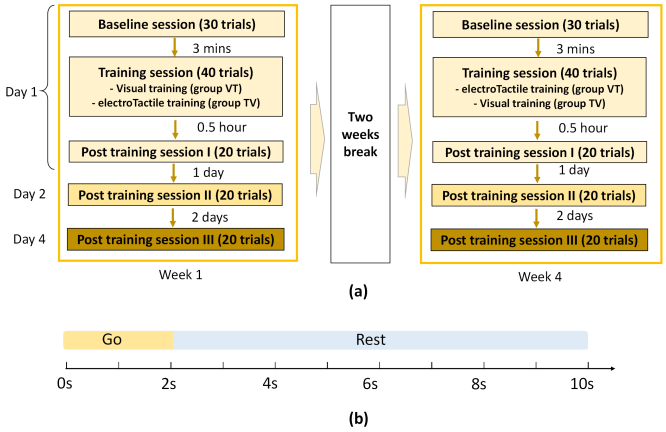


Fig. 6. (a) Timeline of the tongue motor learning experiment with baseline, training, and three post training sessions for both electroTactile-Visual (TV) and Visual-electroTactile (VT) groups; (b) Timer for each trial was shown on the screen. Each trial lasted for 10 seconds. The first 2 seconds was "Go" period where subjects were instructed to reach out to the target as accurately as possible, for at least 1s. The next 8 seconds were for "Rest", where the subjects were instructed to keep their tongue at rest.

III. Experimental Design

A. Human Subjects Recruitment

Eight healthy subjects (4 females and 4 males) participated in the experiment. The protocol of the experiment has been approved by the Texas A&M University Institutional Review Board (TAMU IRB) on March 3rd, 2021 (IRB2018-0912F). The subjects aged between 25-33 years, with an average of 28.5 years. Informed consent was obtained from all subjects.

B. Grouping the Subjects as Visual and Electrotactile Groups

To increase the statistical power and counterbalance the potential learning effect, a crossover design was adopted. Subjects were randomly divided into two groups: the Visual-electroTactile (V-T) group and the electroTactile-Visual (T-V) group, and completed the visual and electrotactile feedback trainings in an opposite order. Also, to further minimize the effect of learning on the results, different part of the electrode array was used for each training (as explained in II-2). For the V-T group, the right three columns of the electrode array were used for the electrotactile training and the left three columns were used for the visual training. For the T-V group, the left three columns of the electrode array were used for the electrotactile training and the right three columns were used for the visual training. Target location was set at the center of the activated 3×3 electrode array. In addition, there was 2-week time gap in between the two training sessions. The V-T group completed the visual training first and the electrotactile training two weeks later, whereas the T-V group completed the electrotactile training first and visual training two weeks later. Fig. 6a shows the detailed timeline/procedure of the experiment.

C. Exp 1: Identification of Stimulation Frequencies

For electrotactile display, the distance information from the target electrode was mapped to the frequency of stimulation (the further the higher). We selected three different frequencies that evoke perceivable and distinct perception, without any discomfort: $f_{high} = 250$ Hz, $f_{mid} = 40$ Hz, and $f_{low} = 3$ Hz. It is based on our prior work showing that stimulation with 10-50 Hz evokes pulsing sensation, whereas stimulation with higher frequency evokes buzzing sensation [50]. To confirm that the perception of three selected stimulation frequencies is distinguished well, subjects were instructed to hold one single electrode in front of their mouth, and use their tongue tip to touch the electrode for around 1 s in each trial. In each trial, the electrode provided an electrical stimulation with one of the three frequencies to the tongue. After each trial, the participants were asked to answer which stimulation frequency they were given among f_{low}, f_{mid}, and f_{high}. This was repeated for 10 times (10 trials), and the electrical stimulations were provided in a pseudorandom order as follow: f_{mid} - f_{low} - f_{high} - f_{mid} - f_{low} - f_{high} - f_{high} - f_{mid} - f_{high} - f_{mid}. Subjects' answers were recorded to confirm the appropriateness of the stimulation frequencies. This task was carried out a week before the second experiment (*i.e.,* tongue pointing task), to minimize any stimulation aftereffect.

D. Exp 2: Tongue Pointing Task

To evaluate the tongue motor learning, we employed a tongue pointing task on the palate. Before the training, we showed the actual dental retainer and the target location to the subjects, and instructed them to touch the target on the palate by their tongue tip as accurately as possible. Each attempt was defined as one trial. Each trial lasted for 2 s, with 8 s break in between. A timer, as in Fig. 6b, was shown on the computer screen for all trials. Once the "Go" sign was on at 0 s, the subjects were instructed to move their tongue to contact the target on the palate by the tongue before the timer reached 1 s, and to return back to the resting position after the "Go" sign was off at 2 s. To avoid any expedient way of learning, subjects were instructed at the beginning of the experiment not to slide, swipe, or contact the upper palatal area by their tongue, during the whole experiment. During the break in between trials, subjects were asked to detach their tongue tip from the palate, and locate the tongue to the resting position. Further, during the whole experiment, we monitored subject's

tongue contact in real time by a separate screen, which the subject couldn't see, to make sure they are approaching the target in a proper way.

For the baseline session, the task was repeated for 30 trials with no electrotactile or visual feedback provided. The training session consisted of two parts, with 20 trials per part, total of 40 trials. And there was a two-minute break between the two parts of the training. Visual feedback was provided by the LEDs on computer screen showing the target location and real-time tongue-palate contact information to the subject. Electrotactile feedback was provided by the electrical stimulation, along with the mechanical protrusion at the target.

To test if electrotactile training provided longer retention than visual training, subjects were asked to complete a series of post training sessions on three consecutive days: 0.5-hour post training at the same day (post training session I), 1-day post training (post training session II), and 3-day post training (post training session III), as shown in Fig. 6a. The post training sessions were performed by the same manner as the baseline, with no sensory feedback provided.

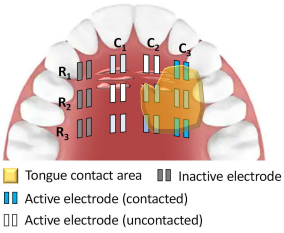
IV. Data Analysis Method

A. Statistical Analysis

To determine the efficacy of the independent factors on dependent variable, and to account for both within-subject and across-subject variabilities, we performed a linear mixed model analysis (SPSS 16, IBM, Chicago, IL, USA) per each experimental result. Both subject and trial were set as random factors. For the independent factor (training type), its effects on the dependent variables (error score, improvement, learning time, and learning speed) were determined independently. We also tested normality of data distribution using the Kolmogorov-Smirnov test of normality. All datasets satisfied the condition of $p > 0.05$ and normality could be assumed. To compare the variation between the baseline measure and post training measures, F-test was used with the hypothesis of the variances of two groups are equal. For all statistical tests, the significance level was set at 0.05 (95% confidence interval). All statistical data were represented as Mean ± STE (standard error) in the experimental result section and all statistical comparison results were represented with the corresponding p values.

B. Assessment of Discriminability Between the Frequencies

To assess discriminability between the three selected frequencies (f_{low} = 3Hz, f_{mid} = 40Hz, and f_{high} = 250Hz), each subject was asked to identify the frequency of the applied stimulation for 10 times (*i.e.,* 10 trials) while the frequency was randomly selected among the three. For each trial, if the subject could identify the frequency correctly, it was counted as one successful trial. For each subject, the discriminability between the frequencies was determined by the percentage of successful trials out of 10 trials. In addition, we asked subjects if they felt any discomfort during the stimulation with any of the three frequencies.



(a)

Contact Matrix

CM_{ij}	C_1	C_2	C_3
R_1	0	0	1
R_2	0	1	1
R_3	0	1	1

(b)

Distance Matrix (normalized)

DM_{ij}	C_1	C_2	C_3
R_1	$\sqrt{2}$	1	$\sqrt{2}$
R_2	1	0	1
R_3	$\sqrt{2}$	1	$\sqrt{2}$

(c)

Fig. 7. An exemplary tongue-palate contact and corresponding contact matrix: (a) tongue contact on the palate; (b) contact matrix; (c) distance matrix.

C. Assessment of Tongue Motor Performance

1) Contact Matrix and Distance Matrix: Two matrices, a contact matrix and a normalized distance matrix, were defined. Both matrices consisted of 9 elements as a 3×3 array. For the contact matrix, each element indicated whether the electrode at row i, column j was contacted ($CM_{ij} = 1$) or not ($CM_{ij} = 0$). For the distance matrix, each element indicated the normalized distance from each electrode to the target, as 0, 1, or $\sqrt{2}$. Fig. 7a shows an example of the tongue contact area on the palate. Fig. 7b is the corresponding contact matrix, and Fig. 7c is the corresponding distance matrix.

2) Error Score: We evaluated subjects' tongue motor performance in each trial by the error score. The Error score was defined as below Eq. 2:

$$Error\ score = \sum (CM_{ij} \times DM_{ij}) \tag{2}$$

where CM_{ij} and DM_{ij} are the value at row i, column j of the contact matrix and the distance matrix, respectively. Lower error score indicated that the tongue was able to point at the target location with a higher accuracy.

D. Assessment of Tongue Motor Learning

1) Learning Curve and Learning Plateau: We adopted the definition of the learning curve and learning plateau as defined in prior works [51], and the below function in Eq. 3 was used to fit the curve and calculate the learning plateau:

$$y = a + \frac{b}{x} \tag{3}$$

where y is the error score, x is the number of trials, a is the lower limit of error score, which was defined as the learning plateau, and b indicates how fast the learning reached the plateau (the smaller the faster).

2) Improvement: The improvement in error score, at training plateau and each trial of the post trainings, was defined as below Eq. 4:

$$Improvement(\%) = \frac{Baseline - Measurederror\ score}{Baseline} \times 100 \tag{4}$$

3) Learning Time: The learning time was defined as the number of trials it takes for a subject to reach 90% level of the improvement obtained at the training plateau.

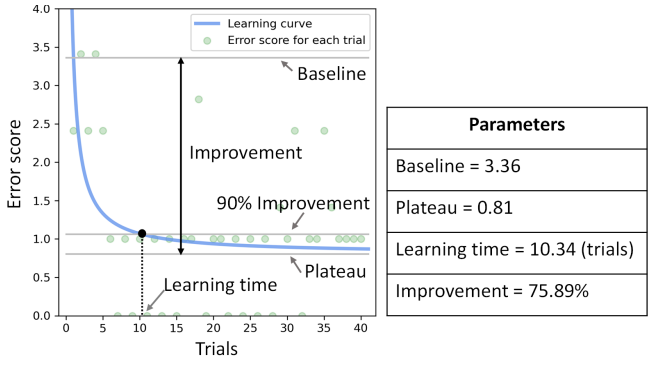


Fig. 8. One subject's learning curve of the training session (left), and corresponding performance evaluation parameters (right).

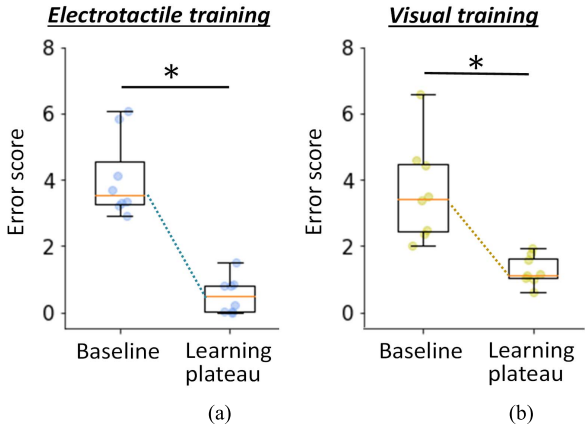


Fig. 9. Error scores measured at the baseline and learning plateau for (a) electrotactile training and (b) visual training (all values are represented as Mean ± STE).

4) Learning Speed: The learning speed was defined as the average reduction in error score per trial till reaching the learning plateau. It is computed as below Eq. 5:

$$Learning\ speed = \frac{Improvement}{Learning\ time} \tag{5}$$

Fig. 8 shows an example of one subject's learning curve during the training and the corresponding performance evaluation parameters.

V. Experimental Result

A. Subjects Successfully Distinguished Three Stimulation Frequencies of 3, 40, and 250 Hz

Regarding the identification of three stimulation frequencies (3, 40, and 250 Hz), we found that all subjects were able to identify the three different stimulation frequencies with a mean accuracy of 92.5%. During the experiment, no discomfort was reported with all three frequencies for all subjects.

B. Tongue Motor Ability of Pointing Target on Palatal Surface Was Improved by Either Visual or Electrotactile Feedback

Figs. 9a and 9b show the result of eight subjects' average error score at baseline and learning plateau, with electrotactile

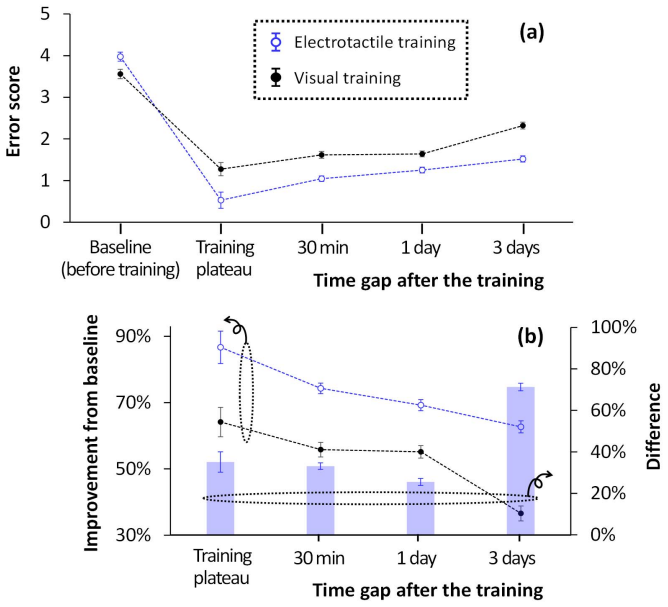


Fig. 10. Overview of (a) average error score of the baseline, training plateau, and post trainings and (b) the improvement retained at post-training sessions (for each of visual and electrotactile trainings) and the difference of improvement in electrotactile training compared to visual training, calculated based on the equation of "(Improvement_electrotactile – Improvement_visual)/Improvement_visual". Statistical test results are not represented on the graphs as it will make the graph too busy. Statistical difference with $p < 0.05$ was found for all combinations except the ones between 30-min post visual training and 1-day post visual training, for both the error score and improvement (all values are represented as Mean ± STE).

training and visual training, respectively. By electrotactile feedback, the average error score reduced significantly from baseline at 3.97 ± 0.11 to 0.53 ± 0.19 at learning plateau ($p < 0.001$). Visual training also significantly reduced the average error score from 3.56 ± 0.11 to 1.27 ± 0.16, ($p < 0.001$). In addition, the variation in error score was significantly reduced in any post-training session, compared to the variation at the baseline measure, for both electrotactile training ($p < 0.001$) and visual training ($p < 0.001$).

C. Retention of Tongue Motor Ability Improvement of Pointing Target on Palatal Surface Was Higher With Electrotactile Training Than Visual Training

The error score and improvement after either tactile or visual trainings were depicted in Figs. 10a and 10b, respectively. Note that statistical test results are not represented on the graphs as it will make the graph too busy. Statistical difference with $p < 0.05$ was found for all combinations except the ones between 30-min post visual training and 1-day post visual training, for both the error score and improvement. Fig. 10a shows the error score for baseline, training plateau, and three post-training sessions. The baseline error score for the electrotactile training sessions was 3.95 ± 0.11, which is statistically larger than the baseline error score for visual training sessions as 3.56 ± 0.11 ($p = 0.006$). Except for the baseline session, the error score of electrotactile training sessions was always statistically lower than that of visual

training sessions. First, subjects reached to a lower error score at the plateau with electrotactile training (0.53 ± 0.19) than visual training (1.27 ± 0.16; $p = 0.004$). On 30-min post training, the error score of electrotactile training was 1.05 ± 0.07, which was statistically lower than the error score for visual training as 1.62 ± 0.08 ($p < 0.001$). On 1-day post training, the error scores were 1.25 ± 0.07 for electrotactile training and was still lower than that of visual training (1.64 ± 0.07; $p < 0.001$). On 3-day post training, the error score of electrotactile training (1.52 ± 0.07) remained lower than that of visual training (2.32 ± 0.08; $p < 0.001$).

Fig. 10b shows the improvement by training compared to the baseline error score (see Eqs. 3 and 4) and retained improvement during the three post-training sessions. First, the improvement during electrotactile training (84.35 ± 5.63%) was statistically larger than the improvement during visual training (61.59 ± 5.06%; $p < 0.001$). Second, the retained improvement after electrotactile training was always statistically larger than the retained improvement after visual training ($p < 0.001$ for all three points of post training). The difference in improvement between the electrotactile and visual trainings became especially largest at 3-day post training, at 62.68 ± 1.81% and 36.59 ± 2.24% respectively, as improvement after electrotactile training is 71.3% larger than that after visual training.

D. The Speed of Learning Tongue Motor Ability Was Not Different Between Electrotactile Training and Visual Training

Fig. 11 shows the normalized learning curves of all subjects for both electrotactile and visual trainings. To compare the learning speed with visual clarity, all learning curves were subtracted by the learning plateau values for each curve, for the error scores of all the normalized learning curves to converge to zero. Based on the averaged learning curves for all subjects in Fig. 11, the learning time with electrotactile training (6.25 ± 1.48) looks shorter than the learning time with visual training (11.27 ± 2.62), but the difference is not statistically meaningful ($p = 0.118$). The same applies to the learning speed. The learning speed with electrotactile training (26.67 ± 10.34%) looks higher than the learning speed with visual training (8.72 ± 2.72%), but the difference is not statistically meaningful ($p = 0.119$).

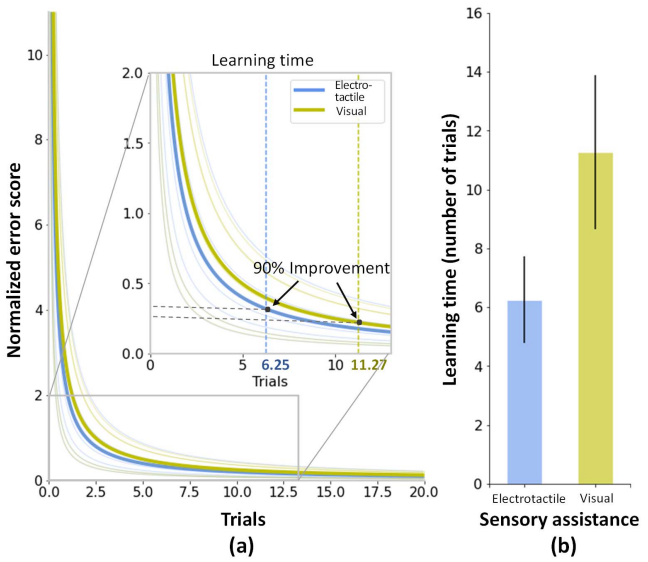


Fig. 11. (a) Learning curve for all subjects, with the normalized error score that converges to zero as a plateau (learning curve subtracted by the learning plateau for each curve), and (b) learning time for both electrotactile and visual trainings (all values are represented as Mean ± STE).

VI. Discussion

A. Limited Tongue Motor Control Ability May Stem From the Limited Proprioceptive Feedback

The experimental results showed that visual or electrotactile assistance enhances tongue motor control ability, which support our first hypothesis that visual or electrotactile training will improve the tongue motor control ability. Also, we observed that the error score got decreased and reached a plateau with less variation compared to the baseline (i.e., subjects' tongue control capability become less dispersed after the training). This suggests that the varying tongue motor capability is due to the varying ability in perceiving the location on the tongue. When no sensory assistance was provided, subjects should mainly depend on the proprioception from tongue muscles to point at a target location on the palate. When visual or electrotactile assistance was provided on top of the proprioceptive feedback, they may have compensated for the compromised accuracy in perceiving the tongue location and enabled subjects to fully enjoy the ability in tongue motor control. This result further suggests that tongue motor training should focus on supplementing the limited accuracy in perceiving the tongue location by proprioceptive feedback.

B. Electrotactile Training May Replace Visual Training to Enhance the Tongue Motor Learning Efficacy

Tongue motor training is commonly practiced by speech therapists, and visual feedback is often employed at the clinic to promote the training efficacy. For instance, SmartPalate system, LinguaGraph, and WinEPG provided real-time visual feedback inside the oral cavity [52]. However, there is a washout effect after the visual motor training [23], [24], which significantly limits the training efficacy and often frustrates both the therapist and patients. Our experiment results suggest that retention of improvement in tongue motor control accuracy is higher with electrotactile training than visual training, which supports our second hypothesis. Our experiment results also suggest that neither learning time nor learning speed is different between the cases of electrotactile training and visual training, which rejects our third hypothesis. Although there is a long way to go to demonstrate the superior efficacy of electrotactile training to visual training on tongue motor learning and its long-term effect, this study made an important step forward to better understand the optimal setting of the tongue motor learning and employ the proper type of sensory assistance.

C. The Underlying Reason for Effective Electrotactile Training Needs to Be Further Investigated

The underlying reason for superior efficacy of electrotactile training to visual training on tongue motor learning is unclear and should be further investigated. It is perhaps because of the neural pathway, as tongue muscles are controlled via the corticobulbar pathway and tactile feedback shares the same pathway, while visual feedback works well for training the limb muscles controlled via the corticospinal pathway [27]. We also speculate that the error-augmented feature of the electrotactile training may have contributed to the enhanced motor training, as the electrical stimulation applied onto the tongue may have provided stronger error signal than visual display [53].

D. Natural Association With the Target Motor Task May Be More Important Than the Amount of Information for the Speed of Motor Learning

Visual training apparently provides more information than electrotactile training, yet subjects did not learn faster with visual training. Although the difference was not statistically meaningful, subjects rather learned faster with electrotactile training. This result suggests that natural association with the target motor task is perhaps more important than the amount of information provided. The language learning process provides insight in tongue motor learning, as the tongue naturally learns new maneuver for novel pronunciation not with visual feedback but with tactile and proprioceptive feedback on the tongue. Study on the sensory augmentation for balance also suggests that natural association with the target motor task is an essential factor for the sensory assistance in improving the motor performance [54]. The importance of natural association to the target motor task, in selecting the type of sensor assistance for motor learning, needs to be further investigated.

E. The Superior Efficacy of Electrotactile Training to Visual Training Is Perhaps Because the Intraoral Space Is Hidden From the Vision

The tongue is hidden inside the mouth, where visual feedback does not ordinarily play a role in intraoral activities. Therefore, in line with the other tongue motor researches, we speculate that people don't have accurate visual map of their intraoral space like the other parts of the body [55], while they do have intraoral somatosensory map. This may explain why the electrotactile training was more effective than visual training on tongue motor learning. Indeed, multiple prior studies support the importance of tactile feedback on tongue motor learning. Tongue is frequently contacting with the palate or teeth for intraoral operations like consonant production. Research on audiovisual speech perception also reported that showing visual representations of tongue movements had very limited effect on subjects' accuracy in identifying speech sounds [56]. Another study showed that electrotactile feedback on the tongue was enough for subjects to recognize the shape of an object at nearly 100% accuracy without any prior training [57]. It would be worth to investigate further on the inaccuracy of the visual map over the intraoral space, and how the inaccuracy of the visual intraoral map is associated with the inferior efficacy of visual training to electrotactile training.

F. Potential Application of Electrotactile Display is Training People Having Issues in Tongue Motor Control During Speech

Electrotactile display can be used to train people having issues in tongue motor control. For example, it can be applied to enhance the effectiveness of speech therapy for non-native speaker or children having apraxia of speech [58]. Electrotactile display might be especially effective for correcting non-standard pronunciation habit of alveolar consonants, as the tongue moves behind the teeth for alveolar consonants where visual display would not be intuitive [59], [60]. It can also be applied to correct stuttering or murmuring, which can hardly be addressed with the current speech therapy techniques. Study on the effect of the electrotactile display for speech therapy would demystify the source of speech problems as well as enhancing the effectiveness of speech therapy.

G. Limitations and Future Direction

Firstly, a small number of subjects participated in this research ($n = 8$) is the limitation of the study. Although we observed strong statistical difference between visual and electrotactile training on the improvement in tongue motor control accuracy, the difference in learning speed would also become statistically meaningful with larger number of subjects. In the next study, we will recruit a larger number of subjects to minimize the effect of personal variation. Secondly, the subjects in this experiment were all healthy and young without any tongue control issue, and therefore they were indeed not in needs of the tongue motor training. In the future study, we will test the system with people in needs of the tongue motor learning, to see whether the electrotactile feedback can help them improve their tongue motor abilities. Thirdly, we did not investigate the potential relationship between the sensitivity to the electrical stimulation and the effect of electrotactile training. As the sensitivity to the stimulation varies among people and changes over aging process, it might affect the efficacy of electrotactile training. Customizing stimulation parameters to adjust the sensitivity would be another interesting direction of research. Fourthly, combination of visual and electrotactile display may further improve the tongue motor control performance and training effect. We will further investigate the synergy between the two types of sensory feedback in our follow-up study. Fifthly, we speculate that the efficiency of the training might be also affected by the target location on the palatal area. It will be interesting to investigate how the target location affects the tongue pointing performance and tongue motor learning. Lastly, we tracked the lasting effect of each training only during three days post training, and how the retention would change after three days will provide importance insight over the effects of different types of sensory assistances. Our next step is to investigate the change of retention after the training over several weeks and even several months, to confirm the

benefit of electrotactile training to be integrated in the current therapies of tongue motor learning.

VII. Conclusion

In this study, we sought insight in designing the effective sensory assistance for the tongue motor learning, and employed a tongue pointing task on palate with visual or electrotactile assistance. Based on the experimental results, we found that the tongue motor learning efficacy can be enhanced by visual or electrotactile assistance, which may compensate for the limited accuracy of original proprioception. We also found that electrotactile assistance is more effective than visual assistance for the tongue motor learning, with consistently stronger retention during the three days post training. We expect that these results will inspire researchers to further investigate the underlying reason of limited efficacy of visual training and the immense potential of the electrotactile training on the tongue motor learning.

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