Department of Veterans Affairs

JRRD Volume 42, Number 5, Pages 705–714
September/October 2005
Journal of Rehabilitation Research & Development

An initial study on lip perception of electrotactile array stimulation

Wei Liu, MS; Hui Tang, PhD*
Department of Electrical and Computer Engineering, University of Missouri–Columbia, Columbia, MO

Abstract—We conducted an initial study on tactile sensory characteristics of the lips by applying electrotactile array stimulation on the center surfaces of the upper and lower lips. We performed experiments of threshold measurement and rating of two-line separation to evaluate the tactile sensitivity and spatial discriminating ability of the lips, respectively. Three stimulator arrays of different sizes presented electrotactile patterns on the lips of eight subjects (six male, two female) to measure the electrotactile performance in relation to stimulator size and spacing. Experimental results showed that the lips required very low intensities for effective electrotactile stimulation. As the stimulator diameter increased from 75 micrometers to 1.55 millimeters, the average stimulation intensity at the threshold level decreased from 12.5 to 6.3 V for the lower lip and from 13.3 to 7.1 V for the upper lip. Meanwhile, the two-line separation rating experiment showed that both upper and lower lips possessed high spatial discriminating ability. The average percentages of correct rating of two adjacent lines ranged from 80.5% to 88.2% on the two stimulator arrays with center-to-center spacing of at least 2.40 mm. In addition, sensitivity analysis indicated that the upper lip slightly outperformed the lower lip in spatial discrimination.

Key words: electrotactile stimulation, lip perception, psychophysical measurement, sensitivity analysis, sensory rehabilitation, sensory threshold, spatial discrimination, tactile aid, tactile display, tactile sensitivity.

INTRODUCTION

Physiology reveals that the tactile sense is a distinct sensory modality, compared with vision and hearing, with its own specialized tactile receptors, nerve fibers, and cortical mapping [1]. This unique sensory modality allows information to be transmitted to the human brain through the tactile channel, which has long been explored in sensory rehabilitation for substitution of the disabled sensory channel (vision and/or hearing) [2–4], and in virtual reality to provide tactile feedback for more realistic perception of virtual environments [5]. Information transmission through the tactile channel is possible with the use of a tactile display, a noninvasive device in direct contact with the skin surface that stimulates the skin with either mechanical or electrotactile stimulation [6]. When implemented as two-dimensional (2-D) stimulator arrays, tactile displays may convey information in the spatial dimension, which can be useful for persons with visual impairments during outdoor navigation and access to graphical computers [7–8]. Collins has demonstrated that a human face or a telephone can be recognized when tactile images of these objects are presented with tactile displays [9]. Spatiotemporal patterns may also be presented with tactile displays, for example, to provide geospatial cues in navigational guidance [10]. In addition to being silent, information coded through the tactile channel can be more intuitive than sound output.

Abbreviations: 2AFC = two-alternative forced choice, 2-D = two-dimensional, ANOVA = analysis of variance.

This material was based on work supported by the University of Missouri Research Board, Columbia, Missouri, grant RB05-053.

*Address all correspondence to Hui Tang, PhD, Assistant Professor; University of Missouri–Columbia, 349 Engineering Building West, Columbia, MO 65211; 573-882-6630; fax: 573-882-0397. Email: tanghu@missouri.edu

DOI: 10.1682/JRRD.2005.02.0051

Vibrotactile and electrotactile displays have been explored for different body regions, such as the back, abdomen, thigh, and fingers [6]. The performance, cost, and portability not only depend on the stimulation methods but also are limited by the sensory characteristics of the skin regions that receive the stimulation. Tactile sensitivity and spatial resolution vary substantially across the human body, primarily because of changes in the density of tactile receptors on different body locations [11]. In the past, the back and abdomen were used as the receptive regions for tactile image conversion [9,12]. However, tactile sensitivity and spatial resolution on these regions are relatively low, despite their relatively large surface area. For example, two-point limen for electrical stimulation on the back was measured in the range of 5 to 10 mm, with voltages around 100 V for adequate stimulation. High spatial discriminating ability was demonstrated on the fingertip with the use of a vibrotactile display called Optacon (Telesensory Systems, Inc, Mountain View, California), which was applied as a reading aid and a tactile mouse [7,13]. However, vibrotactile displays are expensive because of their complex mechanical structures. In addition, vibrotactile displays require high power consumption compared with their electrotactile counterparts [3]. For outdoor and dynamic environments, it is highly desirable that a tactile display be energy efficient, miniaturized, and easy to use, which in turn requires the receptive body region to be highly sensitive to tactile stimulation.

In recent years, the potential of oral structures for tactile applications has drawn attention from researchers because of their relatively large cortical mapping in comparison with their small surface area. This large cortical mapping indicates a high-density distribution of tactile receptors, suggesting that oral sites may be more sensitive and capable of spatial discrimination than other body regions. Past psychophysical studies on force sensitivity did show that the lips and tongue were more sensitive than the palate and the finger [14–16]. In addition, the lips and tongue also demonstrated superior spatial discriminating ability in the detection of grating orientation [17]. Recent studies on electrotactile stimulation further indicated that oral structures required low stimulation intensities for effective electrotactile stimulation, which was demonstrated on the tongue [18–19] and the roof of the mouth [20]. This feature of low-intensity stimulation is highly desirable for wearable tactile aids that demand low power consumption. However, experimental data regarding electrotactile stimulation on the lips has never been obtained. Before the lips could be further explored for tactile display applications, the tactile sensory characteristics of the lips, including electrotactile sensitivity and spatial discriminating ability, should be fully investigated.

In this article, we present preliminary results on electrotactile sensitivity and spatial discriminating capability of the upper and lower lips. We obtained these results by presenting electrotactile patterns on the lips using 2-D stimulator arrays. Because the stimulator size, spacing, and shape are important factors that may affect the perception of the human subjects on electrotactile patterns, three stimulator arrays with different geometrical dimensions were used in the experiments, which in turn provide insight into the design of an electrotactile display with geometrical features suitable for lip stimulation. We performed experiments of threshold measurement and rating of two-line separation on human subjects to study the electrotactile sensitivity and spatial discriminating capability, respectively. The experimental data helps us to understand electrotactile sensation on the lips in general and pave the way for design of lip-based electrotactile displays in the future.

METHODS

The experimental setup used for this study consisted of a stimulator array that presented tactile patterns to the upper or lower lip, and a waveform generator that delivered stimulation waveforms with precisely controlled parameters to active stimulators on the array. The waveform generator also allowed easy selection of patterns, as well as control of stimulation intensities during the experiments. The stimulator array and the waveform generator were connected with a standard 40-pin flat cable. The apparatus and the experimental design are described separately in the following subsections.

Simulator Arrays

Figure 1 shows the three electrotactile arrays (I, II, and III) we used to apply electrotactile stimulation on the lips. Stimulator array II is a flexible device that was originally designed to study electrotactile stimulation on the roof of the mouth and microfabricated with thin-film and electroplating processes [21]. The nickel-electroplated stimulators are 200 μm in height, 700 μm in diameter, and nearly hemispherical in shape. Stimulator arrays I and III

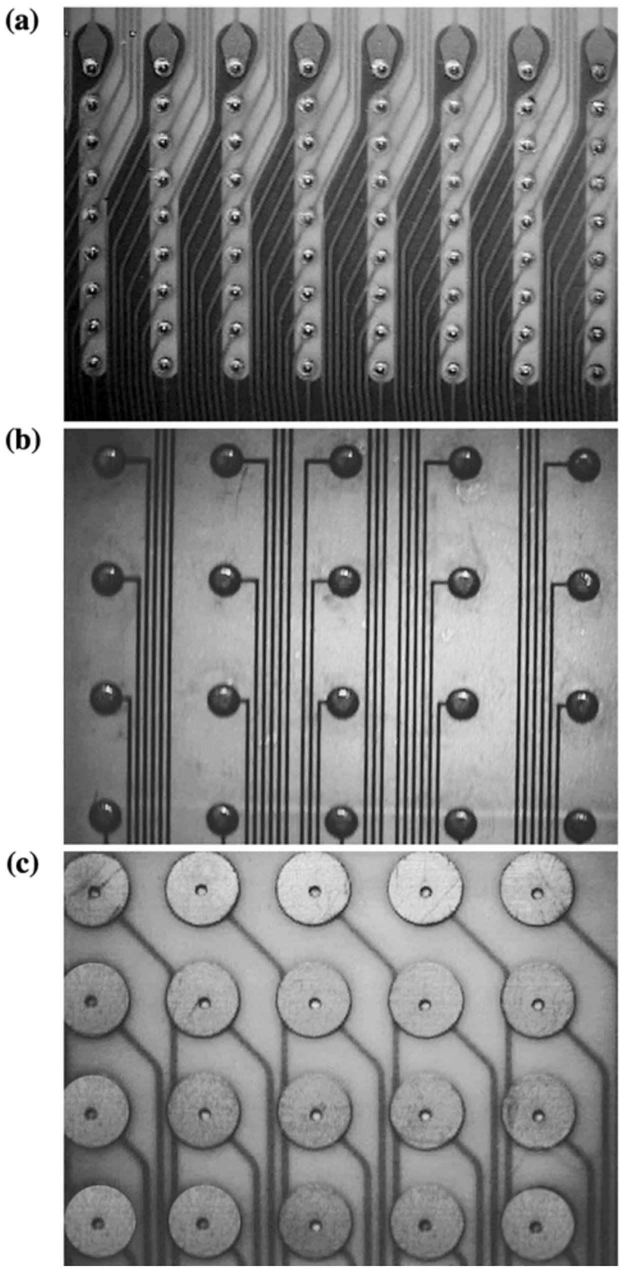

Figure 1.
Three stimulator arrays used to apply electrotactile stimulation on lips: (**a**) array I, (**b**) array II, and (**c**) array III.

were made available from Delphi Connection Systems (Irvine, CA) and Wicab, Inc (University of Wisconsin–Madison, Madison, WI), respectively. The stimulators on array I are nearly round dots 125 µm in height and 75 µm in diameter. The stimulator structure is composed of 1.27 µm-thick gold on top of 2.54 µm of nickel, all on top of 25.4 µm of copper. Array III has gold-coated planar circular stimulators about 1.55 mm in diameter. Dimensions regarding spacing among stimulators are listed in the two-line separation experiment described in the "Procedure" section. We used the middle portion of each stimulator array, consisting of 4 × 4 stimulators, to present electrotactile patterns. During the experiments, we placed the device at the center of the designated lip, and subjects maintained the position by closing their lips, as shown in **Figure 2**. Subjects were instructed to grab the connection cable to the array assembly with one hand for additional support.

Waveform Generator

We used a waveform generator provided by Wicab, Inc, at the University of Wisconsin–Madison (Madison, WI) to deliver the stimulation waveforms to the individual stimulators on the arrays. The system can generate positive and monophasic voltage pulses with zero net direct current. Up to 144 stimulators may be individually activated with a set of waveform parameters stored prior to the experiments. For quick recovery of ionic balance at the stimulation site, we kept the pulse-on duration less than 0.5 ms [6]. Each active stimulator received an identical stimulating waveform, as shown in **Figure 3**. The pulse train contained bursts of three 24 µs pulses, where the pulse onsets were separated by 5 ms and the burst onsets were separated by 20 ms. There was a delay of 139 µs from one activated stimulator to its activated neighbor so that the current flow to the skin at any instant in time was limited to one stimulator. The subject or the

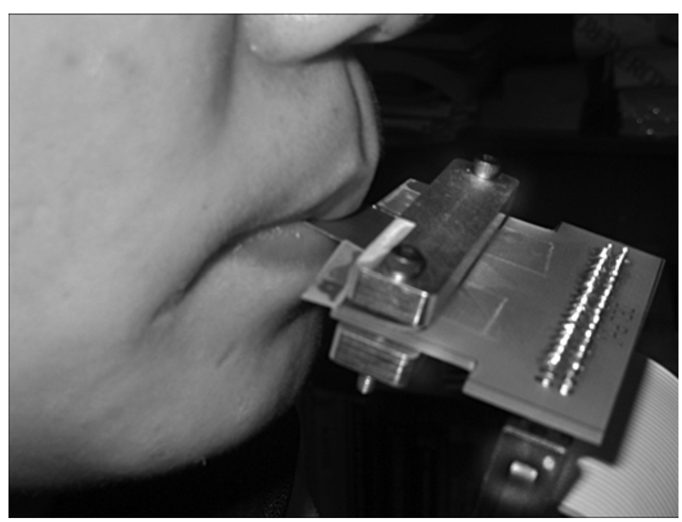

Figure 2.
Subject holding stimulator array between lips with electrotactile stimulation presented on lower lip.

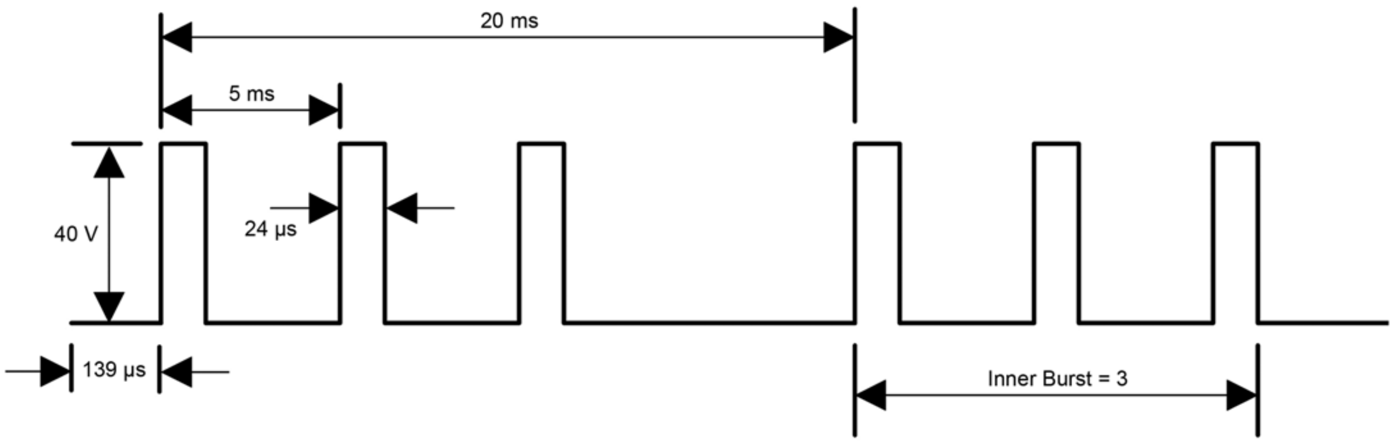

Figure 3.
Stimulation waveform delivered through active stimulator.

experimenter could adjust the stimulation intensity in the range of 0 to 40 V during the experiment.

Procedure

Eight sighted volunteers (six male, two female), with six young adults aged 25 to 31 and two seniors aged 64 and 65, were recruited for the experiments. The experiments were divided into two phases, during which the lower and upper lips were studied. Because of the psychophysical nature of the experiments, in which perceptual results may change in response to different skin conditions, room environments, and even subject emotions, the same measurements were repeated on each subject on different days. Specifically, each subject made three visits in each phase, with at least 24 hours between consecutive visits. Each visit lasted about 1.5 hours and contained six miniature sessions, within which the threshold measurement and rating of two-line separation were carried out on each of the three arrays described earlier. A resting period of about 5 min was arranged after each session. The resting periods between sessions and the separation time between visits were intended to minimize any carryover effects from prolonged stimulation.

Threshold Measurement

We investigated the electrotactile sensitivity of the lips by measuring the intensities of electrotactile stimulation just noticeable to human subjects. We used a 3 × 3 solid square pattern containing a total of nine dots at the center of a stimulator array as the test pattern. We used an intensity of 4 V as the initial value, and then increased it by 4 V each time until the subject could definitely feel the stimulation. In cases in which the subject felt numb or felt no electrotactile sensation, he or she was instructed to rest 10 to 15 s and relocate the stimulator array on the designated lip. After the subject was certain of the perception of the electrotactile stimulation, we used a psychophysical technique called two-alternative forced choice (2AFC) to track the sensory threshold.

The 2AFC approach tracks the sensory threshold through a number of trials, and it removes observer's bias from a human subject by presenting two intervals in each trial, with one interval containing no stimulus [22]. In this case, one interval contained the square pattern, and the other was null. A subject was asked to identify which interval contained the stimulus. Depending on the response from the subject, we adjusted the intensity of stimulation accordingly. The intensity was increased following one incorrect response and decreased following two consecutive correct responses. For each reversal, the step size was half of the previous one. This method tracks the threshold at which the stimulation can be detected with a possibility of 71 percent. The minimum step size was 0.4 V. At the end, the working-level intensity at which perception was comfortable and strong was recorded as well.

Rating of Two-Line Separation

In the two-line separation rating experiment, subjects attempted to rate the spacing between two columns of activated stimulators, with the stimulation intensity set at the working level for each subject. The line patterns were formed in the direction vertical to the mucocutaneous junction line of the lips. We used three patterns in the rating experiment, as shown in **Figure 4**. Pattern 0 is

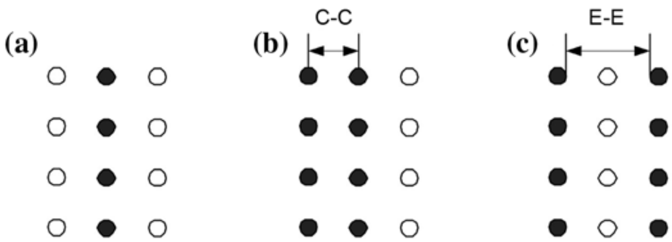

Figure 4.
Two-line patterns with spacing of (**a**) 0, (**b**) 1, and (**c**) 2 for two-line separation rating experiment, with center-to-center (C-C) and edge-to-edge (E-E) distance illustrated.

actually one line, equivalent to a two-line pattern with 0 spacing; pattern 1 consists of two adjacent columns of active stimulators, corresponding to a spacing of 1 between two lines; pattern 2 has one inactive column between two active ones, corresponding to a spacing of 2 between two lines. **Table 1** shows the center-to-center distance and the edge-to-edge distance for spacings of 1 and 2 on each array. For each pattern presented, a subject was asked to identify the pattern number by pointing it out from a list of corresponding visual patterns on a sheet.

Before rating the separation of two-line patterns, each subject had a brief training session to become familiar with patterns 0 to 2. In a formal session for each array, patterns 0 to 2 were presented randomly, with about 10 to 16 repetitions for each pattern. After the subject picked a pattern number in each trial, the experimenter gave feedback on whether the subject's identification matched the actual pattern presented. The stimulation voltage could be adjusted at any time and no time constraint was imposed for each trial. However, the number of repetitions varied depending on how fast a subject responded, so that each visit lasted approximately the same amount of time as scheduled.

RESULTS

Sensory Thresholds and Working-Level Intensities

The staircase 2AFC approach we used for threshold measurement allowed a subject to experience stimulation at various intensity levels, from very weak to very strong. When stimulation intensity was increased progressively, the perception as described by the subjects changed from no sensation, to itching, to strong vibration, to a numbing sensation. Subjects used finger gestures to signal which interval contained the stimulus or to signal that nothing was felt. The stimulation intensities were recorded as the voltage amplitude of the pulse trains delivered to active stimulators.

Table 2 shows the sensation thresholds as well as working-level intensities averaged over three visits for individual subjects on the different arrays (subjects 7 and 8 are the seniors). The results indicated that the sensory threshold-level and working-level intensities were greatly affected by the stimulator size, and both decreased as the stimulator size increased. The mean threshold values averaged among all subjects decreased from 12.5 to 6.3 V

Table 1.
Center-to-center (C-C) and edge-to-edge (E-E) distances (mm) of two columns with different spacing on the three arrays.

Spacing	Array I		Array II		Array III	
	C-C	E-E	C-C	E-E	C-C	E-E
1	1.53	1.46	2.54	1.84	2.40	0.85
2	3.07	3.00	5.08	4.38	4.80	3.25

Table 2.
Average threshold and working levels (in volts) for each subject on each array.

Subject	Array I		Array II		Array III	
	T	W	T	W	T	W
Upper Lip						
1	13.5	19.9	11.1	16.0	8.1	13.1
2	12.7	19.3	10.9	15.2	8.7	12.4
3	14.1	19.6	8.5	15.5	4.3	10.4
4	13.3	20.4	11.2	17.1	8.5	14.1
5	10.7	17.1	8.5	12.5	4.8	9.2
6	12.9	20.1	10.4	15.2	6.3	11.3
7	14.5	21.5	10.8	17.2	8.9	17.2
8	14.4	19.8	10.7	14.4	7.6	12.4
Average	13.3	19.7	10.3	15.4	7.1	12.5
Lower Lip						
1	15.7	20.5	11.2	15.1	8.3	12.3
2	10.5	17.7	7.2	12.0	5.6	8.7
3	10.4	17.2	6.1	14.3	6.0	11.3
4	14.0	21.6	9.5	14.4	6.3	9.6
5	10.1	19.3	5.9	12.3	4.7	9.1
6	13.5	20.0	8.0	13.1	5.2	8.4
7	15.7	22.2	11.5	17.1	8.0	13.2
8	10.4	16.3	8.3	14.7	6.1	10.4
Average	12.5	19.4	8.5	14.1	6.3	10.4

T = threshold level, W = working level.

for the lower lip and from 13.3 to 7.1 V for the upper lip. In addition, the average intensities required for working-level stimulation decreased from 19.4 to 10.4 V for the lower lip and from 19.7 to 12.5 V for the upper lip. The relationship between stimulation intensities and stimulator size is depicted in **Figure 5**.

We performed a two-factor analysis of variance (ANOVA) with repetitions (α = 0.05) to analyze the significance of different factors on threshold variation (**Table 3**). In this analysis, we considered location of stimulation (upper or lower lip) and array as factors, and

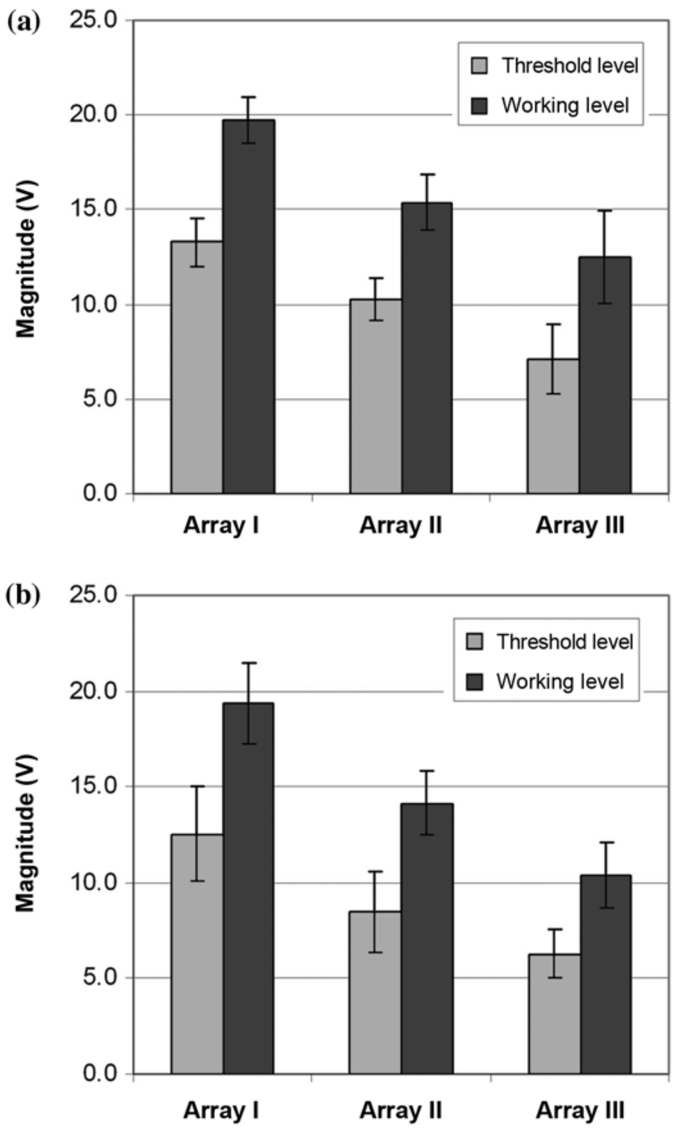

Figure 5.
Average intensities at threshold and working levels on (**a**) upper lip and (**b**) lower lip.

threshold values from different subjects were taken as repetitions. As shown in **Table 3**, the factor "array" has a very significant effect on the threshold variation (p < 0.0001), while location of stimulation is marginally significant (p = 0.03).

Two-Line Separation

We used two statistical measures on the experimental results to indicate the spatial discriminating capability of the upper or lower lip. One measure is the percentage of correct rating on any of the three patterns, and the other is the sensitivity index that quantifies how two patterns differ from each other in the sensory space. The average percentages of correct rating on the three arrays are shown in **Figure 6**, with a significant increase from array I to array II for all three patterns. On the upper lip, it increased from 77.2 to 94.8 percent for pattern 0, from 71.6 to 88.2 percent for pattern 1, and from 75.4 to 85.1 percent for pattern 2. On the lower lip, these increases were 68.7 to 90.0 percent, 58.9 to 80.5 percent, and 71.9 to 86.7 percent, respectively. However, the difference in percentages of correct perception between arrays II and III was not significant, and the separations between two lines were well identified on both arrays II and III, with the percentages of correct rating all above 80 percent.

One can obtain the sensitivity index on a pair of two-line patterns by applying the signal detection theory [22], which assumes that the response for any physical parameter (i.e., the spacing between two lines) is a random variable with a Gaussian distribution over the sensory space. The sensitivity index over two patterns (i and j) is the distance between the two means of the Gaussian distributions corresponding to these two patterns, which can be calculated from the hit rate, the possibility for which pattern j is correctly identified, and the false alarm rate,

Table 3.
Two-factor analysis of variance with repetitions on threshold measurements (α = 0.5).

Source of Variation	SS	*df*	MS	*p*-Value
Location	15.45	1	15.45	0.0295
Array	308.53	2	154.27	0.0000
Interaction	2.76	2	1.38	0.6379
Within	127.68	42	3.04	—
Total	454.43	47	—	—

SS = sum of squares.
df = degree of freedom.
MS = mean square.

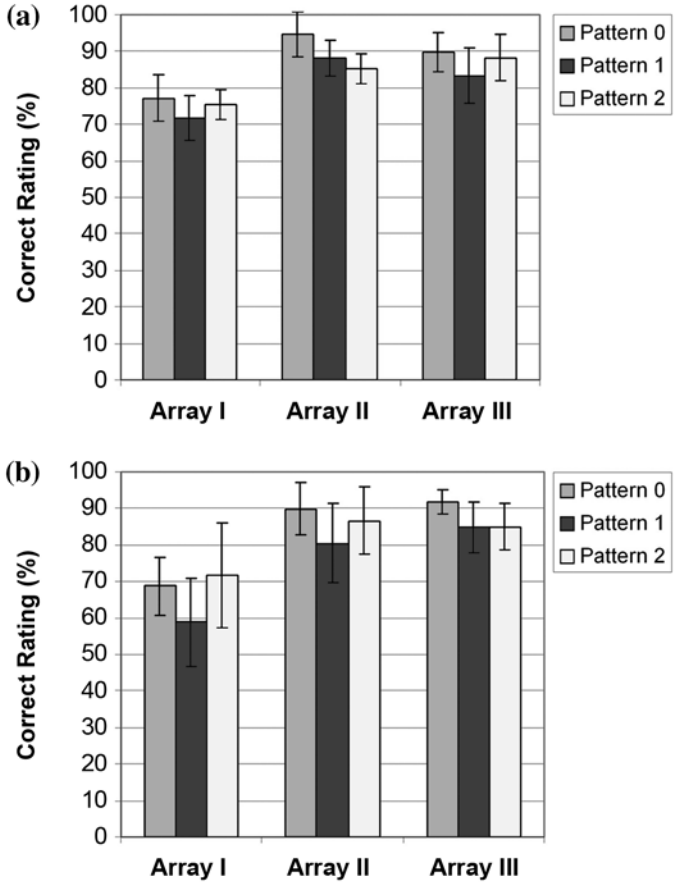

Figure 6.
Average percentages of correct rating of two-line separation patterns among all subjects on each array: (**a**) upper lip and (**b**) lower lip.

the possibility for which pattern i is falsely identified as pattern j. For this rating experiment involving multiple patterns, the effect of intermediate patterns needs to be included in the calculation of the hit and false alarm rates. To evaluate the sensitivity between patterns 0 and 1, a hit is defined as an occurrence in which pattern 1 was rated as pattern 1 or 2, and a false alarm as an occurrence in which pattern 0 was rated as pattern 1 or 2. For one to evaluate the sensitivity between patterns 1 and 2, a hit is defined as an occurrence in which pattern 2 was correctly identified, and a false alarm as an occurrence in which pattern 1 was rated as pattern 2. The sensitivity (d') over the difference between patterns i and j is written as

$$d'(i, j) = f^{-1}(HR(i, j)) - f^{-1}(FR(i, j)) \quad ,$$

where $f^{-1}()$ is the inverse function of the standard normal cumulative distribution $f(x)$, HR is hit rate, and FR is false alarm rate. The sensitivity indices (d') for two patterns with adjacent feature size on both upper and lower lips are shown in **Table 4**.

DISCUSSION

The experimental results on sensory threshold-level and working-level intensities indicate that both the upper and lower lips are extremely sensitive to electrotactile stimulation. The threshold values on array III, ranging from 4.3 to 8.9 V for the upper lip and from 4.7 to 8.3 V for the lower lip, are the lowest reported so far for electrotactile stimulation. These values are slightly lower than those on the tongue (around 5 to 15 V) [18], which Bach-y-Rita et al obtained using relatively bigger stainless-steel stimulators and the same stimulation waveform parameters, suggesting that both the lips and tongue are among the most sensitive sites for electrotactile stimulation. Comparison between electrotactile sensitivity on the lips and the roof of the mouth can be made with examination of the threshold values on array II, because array II has been used for threshold measurement on the lips as well as the roof of the mouth [10]. The upper and lower lips required threshold-level intensities around 8.5 to 11.2 V and around 5.9 to 11.5 V, respectively—about half the intensities required for threshold sensation on the roof of the mouth with the same array (10 to 20 V). In addition, the working-level intensities for lip stimulation averaged only around 12.5 V for the upper lip and 10.4 V for the lower lip (on array III). This low-intensity requirement makes it more promising to miniaturize a lip-based tactile display with integrated electronics that can be applied easily between the lips with minimum cosmetic alteration on the appearance of a user.

Table 4.
Sensitivity (d') on the difference between patterns 0 and 1 and between patterns 1 and 2.

Lip	Array I Patterns		Array II Patterns		Array III Patterns	
	1	2	1	2	1	2
Upper						
Pattern 0	1.53	—	3.13	—	2.49	—
Pattern 1	—	2.10	—	2.69	—	2.66
Lower						
Pattern 0	1.11	—	2.56	—	2.48	—
Pattern 1	—	1.81	—	2.30	—	2.21

While different body regions may exhibit drastically different sensitivity to electrotactile stimulation, the stimulator size can also affect the stimulation intensities to a great extent. As demonstrated on the lips, when the stimulator size decreased, the thresholds as well as the working-level intensities all increased. The significance of stimulator size is shown in an ANOVA with the *p*-value far below 0.0001 (**Table 3**). The correlation between stimulation intensities and the stimulator size can be attributed to the contact resistance, which would decrease with increased contact area between a stimulator and the skin. However, this does not mean arbitrarily large stimulators should be used. Since stimulator size also limits the density of the stimulator array within a given area, one would prefer an electrotactile array that has smaller stimulators but is still capable of stimulating good tactile sensation without significantly increasing the sensation thresholds. In the case of lip stimulation, we believe the optimum size of the stimulators should be between arrays II and III for adequate stimulation at low intensities.

The spatial resolution of the lips is another factor that will limit the density of an electrotactile stimulator array. In the results from the two-line separation experiment as shown in **Figure 6**, rating of patterns 0 to 2 was quite accurate when arrays II and III were used, and performance did not significantly improve from array II to array III. Here, pattern 1 usually received the lowest correct rating, because it could be mistaken for either pattern 0 or pattern 2. The sensitivity (d') in **Table 4** indicates that the difference between patterns 0 and 1, and between patterns 1 and 2 could be well resolved on arrays II and III. The rating performance on array I was mixed among subjects, suggesting that the stimulator size and spacing of array I were not adequate. The rating performance on array I can be further evaluated using sensitivity (d'). While the upper lip could marginally resolve the difference between patterns 0 and 1 ($d' = 1.53$), the lower lip did not show this capability on array I, with a sensitivity of only 1.11 on patterns 0 and 1. In addition, the sensitivity indices show that the spatial discriminating performance on array II is better than that on array III, although the average percentages of correct rating on these two arrays were very close. In conclusion, a center-to-center spacing of 2.40 mm between adjacent stimulators is adequate for separate perception on two adjacent active columns.

Finally, more comments can be made regarding the perceptual difference between the upper or lower lip on electrotactile array presentation. **Table 2** shows that the upper lip often required slightly higher stimulation intensities for threshold- and working-level perception, and the results of the two-factor ANOVA on threshold values shown in **Table 3** also suggest that the threshold variation between the upper and lower lips was somewhat significant. However, the upper lip achieved slightly better performance in resolving spatial patterns, as indicated in the experiment of two-line separation rating. In general, the upper lip generated higher average percentages of correct rating, as shown in **Figure 6**. Sensitivity analysis in **Table 4** also indicates higher sensitivity (d') on the upper lip in all categories of comparison, suggesting that the upper lip is more capable of spatial discrimination.

CONCLUSIONS

These psychophysical experiments on human subjects demonstrated that the upper and lower lips possessed high sensitivity to electrotactile stimulation. Average threshold intensities were as low as 6.3 V on the lower lip and 7.1 V on the upper lip, based on an array of stimulators 1.55 mm in diameter. Strong and comfortable perception of electrotactile stimulation may be obtained on the lips, with average working-level stimulation intensities as low as 10.4 V on the lower lip and 12.5 V on the upper lip (using array III). Decreasing stimulator size increased sensory threshold-level as well as working-level stimulation intensities. The experimental results in two-line separation rating suggest that both the upper and lower lips possess excellent spatial discriminating capability, with the upper lip slightly more sensitive to spatial difference. In conclusion, lips—especially the upper lip—are very useful sites for application of energy-efficient and miniaturized electrotactile aids in mobile environments.

ACKNOWLEDGMENT

We would like to thank Drs. Mitch Tyler and Kurt Kaczmarek at the University of Wisconsin–Madison, Madison, Wisconsin, for providing the waveform generator and array III. We would also like to thank Bill Crumly of Delphi Connection Systems Irvine, California, for providing array I.

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Submitted for publication February 24, 2005. Accepted in revised form June 23, 2005.