LipNotif: Use of Lips as a Non-Contact Tactile Notification Interface Based on Ultrasonic Tactile Presentation

Arata Jingu
The University of Tokyo
Japan
jingu@hapis.k.u-tokyo.ac.jp

Takaaki Kamigaki
The University of Tokyo
Japan
kamigaki@hapis.k.u-tokyo.ac.jp

Masahiro Fujiwara
The University of Tokyo
Japan
Masahiro_Fujiwara@ipc.i.u-tokyo.ac.jp

Yasutoshi Makino
The University of Tokyo
Japan
yasutoshi_makino@.k.u-tokyo.ac.jp

Hiroyuki Shinoda
The University of Tokyo
Japan
hiroyuki_shinoda@k.u-tokyo.ac.jp

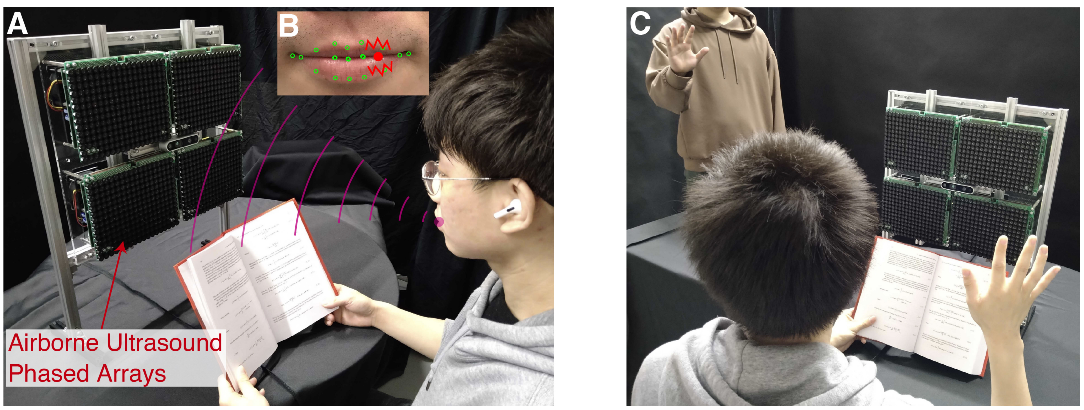

Figure 1: LipNotif is a non-contact tactile notification system that uses airborne ultrasound tactile presentation to lips. (A) Our prototype system consists of a depth camera and airborne ultrasound phased arrays. LipNotif allows the user to receive information using only lips without sight, hearing, or hands. (B) The system automatically recognizes the position of the lip landmarks (green). This information is used to determine the point to be stimulated (red). (C) LipNotif can intuitively convey information, such as directions and emotions. The figure shows a man reading his book and holding it with his hand while listening to music. He was unaware of his surroundings. With a strong stimulus to the left side of the lips, he can notice that an urgent visitor has arrived on the left side.

ABSTRACT

We propose LipNotif, a non-contact tactile notification system that uses airborne ultrasound tactile presentation to lips. Lips are suitable for non-contact tactile notifications because they have high tactile sensitivity comparable to the palms, are less occupied in daily life, and are constantly exposed outward. LipNotif uses tactile patterns to intuitively convey information to users, allowing them to receive notifications using only their lips, without sight, hearing, or hands. We developed a prototype system that automatically recognizes the position of the lips and presents non-contact tactile sensations. Two experiments were conducted to evaluate the feasibility of LipNotif. In the first experiment, we found that directional information can be notified to the lips with an average accuracy of ± 11.1° in the 120° horizontal range. In the second experiment, we could elicit significantly different affective responses by changing the stimulus intensity. The experimental results indicated that LipNotif is practical for conveying directions, emotions, and combinations of them. LipNotif can be applied for various purposes, such as notifications during work, calling in the waiting room, and tactile feedback in automotive user interfaces.

UIST '21, October 10–14, 2021, Virtual Event, USA

ACM ISBN 978-1-4503-8635-7/21/10.
https://doi.org/10.1145/3472749.3474732

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

mid-air haptics, notification, lip

ACM Reference Format:
Arata Jingu, Takaaki Kamigaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2021. LipNotif: Use of Lips as a Non-Contact Tactile Notification Interface Based on Ultrasonic Tactile Presentation. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21), October 10–14, 2021, Virtual Event, USA.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3472749.3474732

1 INTRODUCTION

This paper proposes LipNotif, a non-contact tactile notification system that uses airborne ultrasound tactile presentation to lips (Fig. 1). LipNotif allows users to receive non-contact tactile notifications using only lips, without sight, hearing, or hands.

Tactile notifications can intuitively convey information such as directions and emotions to users by using various tactile patterns without their eyes or ears. A variety of tactile notification methods have been proposed, including graspable devices [1, 65] and wearable devices [15, 22, 24, 25, 32, 33, 43, 44, 48, 55]. All these methods require the skin to be in contact with the device.

Non-contact tactile notifications allow users to receive information without physical contact with tactile devices. Airborne ultrasound tactile presentation [45] is a non-contact tactile presentation method that uses airborne ultrasound phased arrays (AUPAs). It can present tactile sensations with high spatial (8.5 mm at 40 kHz carrier waves) and temporal resolutions (1ms in this study) from a distance of 40 cm (in this study). Previous studies have focused on the palms as the main targets for non-contact tactile notification using airborne ultrasound tactile presentation [41, 42, 51]. When considering non-contact tactile presentation to the hands from a distance, there are two issues. The first is that the hands are constantly used for many other tasks in daily life, such as holding, grasping, and manipulating objects. The second is that the fingertips and palms, which are the most sensitive parts of the hands, are often facing or closing inward, even if they are not doing anything, making it difficult to stimulate them from the outside.

We focused on airborne ultrasound tactile presentation to lips. They have high tactile sensitivity comparable to the palms. In addition, c ompared to the palms or fingertips, the lips are constantly exposed outward (see Section 3.6 about masks) and are less occupied in daily life. In terms of the balance between tactile sensitivity and occupancy, lips can be the effective place to receive non-contact tactile notifications from the outside.

We developed a prototype system that automatically recognizes the position of the lips and presents non-contact tactile sensations. Two experiments were conducted to evaluate the feasibility of LipNotif. In the first experiment, we found that the directional information can be notified to the lips with an average accuracy of $\pm$ 11.1° in the 120° horizontal range. In the second experiment, we could elicit significantly different affective responses by changing the stimulus intensity. The experimental results indicated that LipNotif is practical for conveying directions, emotions, and combinations of them. LipNotif can be applied for various purposes, such as notifications during work, calling in the waiting room, and tactile feedback in automotive user interfaces.

This paper offers the following contributions:

(1) Proposing a new concept: the lip-based notification using non-contact tactile presentation.
(2) Evaluating the ability of lips in tactile notifications (direction identification and affective responses).
(3) Describing specific applications of non-contact tactile notifications to lips.

2 RELATED WORK

This study consists of three research fields: mid-air haptics, tactile stimulation of lips, and tactile notification. We clarify the position of our study after summarizing these fields.

2.1 Mid-Air Haptics

Mid-air haptic technology, which provides non-contact tactile stimulation to users, is gaining popularity. Different mid-air tactile presentation methods have been proposed, including wind blowing [31, 46, 67], air vortex rings [16, 54], lasers [30], electric arcs [56], and AUPAs [8, 21, 23].

Airborne ultrasound tactile presentation is a non-contact tactile presentation method that uses AUPAs. This technology uses a phenomenon called acoustic radiation pressure, which occurs when an object blocks high-density ultrasonic waves. It provides a tactile sensation by modulating ultrasonic waves to match human tactile perception characteristics. The most basic modulation type is sinusoidal amplitude modulation (AM). In AM, the output intensity changes temporally with a sine wave of a certain frequency. Airborne ultrasound tactile presentation has been applied in diverse fields, including mid-air screens [38], virtual reality [50], and mediating emotions [41]. Rakkolainen et al. conducted a more detailed survey on this technology [45].

2.2 Tactile Stimulation of Lips

Lips have high tactile sensitivity. They had a two-point discrimination threshold of approximately 6 mm [66], which was approximately the same as that of the palms [66], lower than that of the arms [66] and other facial parts [53]. Another study showed that the two-point discrimination threshold of the back of the hands was higher than that of the palms [36].

Lips had three types of mechanoreceptors (Ruffini corpuscles, Meissner corpuscles, and Merkel cell disks) [53, 62]. Lips had the lowest detection threshold of contact mechanical stimulation in between 30 and 60 Hz [5], which was considered to be determined by the Meissner corpuscles. Several methods for tactile presentation to lips have been studied so far, including vibrations of straws [19], vibrations of servo motors embedded in silicone rubber [49], electrotactile stimulation [34], and wind blowing [31, 46, 47, 67].

Jingu et al. investigated the tactile perception characteristics of lips in ultrasound tactile presentation [26]. The lowest tactile thresholds were achieved at the valley-shaped area of the lips in terms of location. It would be due to the multiple reflections of ultrasonic waves in the valley-shaped structure between the upper and lower lip. In terms of modulation frequency, the stimulation at 40 Hz was easier to detect than at 5 Hz and 200 Hz. This result was consistent with the case of contact tactile stimulation.

2.3 Tactile Notification

Tactile presentation is a practical notification method. By manipulating different tactile parameters, abstract messages can be conveyed

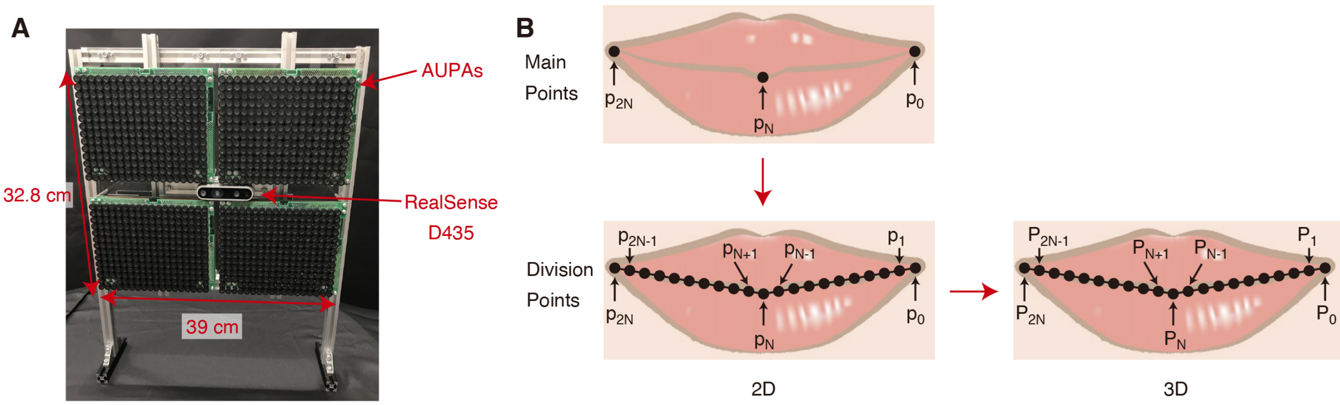

Figure 2: (A) Hardware configuration. (B) Calculation of division points.

to users [7]. To date, many wearable tactile notification devices have been proposed. Most of them are wrist-worn devices that use a wide variety of modalities, such as vibrotactile [33], squeeze [15, 44], dragging [22], thermal [43], and multimodal [55]. In addition to wrists, finger-worn [24, 25, 48] and ear-worn [32] notification devices have been developed.

Some papers have reported non-contact tactile notifications to palms using ultrasonic cues [41, 42, 51]. Sand et al. investigated whether the palm could discriminate between six ultrasonic tactile stimuli [51]. A few studies have examined ultrasonic cue presentations on facial regions other than the lips. Gil et al. compared the perception of ultrasonic cues at three facial sites (cheek, above the brow, and above the bridge of the nose) [14]. Mizutani et al. compared the vibrotactile thresholds and reaction times between six facial sites [37].

2.4 The Position of Our Study

To the best of our knowledge, LipNotif is the first to consider the use of lips in non-contact haptic cues. As described before, the lips are suitable as a stimulus site to present tactile notifications because they have high spatial resolution and are not occupied by other tasks unlike the hands. Despite these advantages, lips have received no attention as targets for non-contact haptic cues. This is considered to be due to the hygienic issues in common contact tactile presentation. In this study, we overcome this problem by remotely stimulating the lips with AUPAs, and have developed a prototype for lip-based information presentation. AUPAs have a sufficiently high spatiotemporal resolution for designing different cue patterns. In addition, AUPAs can cover a frequency range that is effective for tactile presentation to the lips (30–60 Hz). We investigate the ability of the lips as a non-contact tactile notification interface using ultrasonic tactile presentation. This paper focuses only on lips among the facial parts because they are by far the most sensitive in the face [53], and they have not been investigated at all in past studies.

LipNotif does not require users to bring or wear any special equipment, or install any additional software program on their computers or smartphones. Additionally, LipNotif only uses the lips, not the eyes or ears. Therefore, the proposed method is even more powerful when the users do not want to wear the extra devices or use their eyes and ears for other purposes.

3 IMPLEMENTATION

3.1 Area to Present the Ultrasound Focal Point

In this study, we targeted the ultrasonic focal point on the valley-shaped area between the upper and lower lip. This is because, as mentioned in Section 2.2, the lowest tactile threshold was achieved at that area.

3.2 Hardware Configuration

Fig. 2 (A) shows the hardware configuration of the prototype system. We used a depth camera (Intel RealSense D435) for lip tracking and AUPAs for the ultrasonic tactile presentation to the lips. The AUPAs used in this study [58] were composed of 996 ultrasonic transducers.

The AUPAs have a sufficiently high temporal and spatial resolution for designing different tactile patterns. The device can update the amplitude and phase of each transducer's output at a maximum of 1 kHz. The diameter of an ultrasonic focal point is approximately 8.5 mm at 40 kHz carrier waves, which corresponds to the spatial resolution. The focal point can be converged up to a distance roughly equal to the aperture of the AUPAs [2]. Therefore, the effective presentation distance in the proposed system is approximately 40 cm. However, the effective presentation distance can be increased to 1–1.6 m by increasing AUPAs or using a concave reflector, as described in Section 6.2.

3.3 Software Processing Flow

The software processing flow was mainly divided into two parts: calculation of the 3D coordinates of the division points on the lips and the presentation of ultrasonic cues.

The 3D coordinates of the division points were automatically calculated based on the information from the depth camera (Fig. 2 (B)). The number of divisions varied in each experiment. We assume that we will obtain 2N+1 division points in total (N is a natural number ≥ 1). First, the image acquired from the RGB camera was processed by Dlib facial landmark detector [29] to acquire the 2D coordinates of three main points of lips (the left commissure

($p^L = p_0$), center ($p^C = p_N$), and right commissure ($p^R = p_{2N}$)). By dividing the straight line from the left commissure to the center and the straight line from the center to the right commissure into N equal parts, the 2D coordinates ($\vec{p_i} = (p_{ix}, p_{iy})^\mathsf{T}$) of the 2N+1 division points were obtained as:

$$\vec{p_i} = \begin{cases} \frac{i}{N}\vec{p^C} + \frac{N-i}{N}\vec{p^L} & (i \le N) \\ \frac{i-N}{N}\vec{p^R} + \frac{2N-i}{N}\vec{p^C} & (i > N) \end{cases} \tag{1}$$

By combining them with the depth information (z(x, y)) from the depth sensor, we calculated the 3D coordinates ($\vec{P_i} = (P_{ix}, P_{iy}, P_{iz})^\mathsf{T}$) of each division point. Setting the focal length of the RGB camera as (f_x, f_y) and the optical center as (c_x, c_y), the simplified formula is as follows (for more details, see "rs2_deproject_pixel_to_point" function in the RealSense library):

$$\vec{P_i} = z(p_{ix}, p_{iy}) \times \left(\frac{p_{ix}-c_x}{f_x}, \frac{p_{iy}-c_y}{f_y}, 1\right)^\mathsf{T} \tag{2}$$

From the 3D coordinates of the division points, we selected the point to be stimulated according to the purpose of each experiment. Each transducer of the AUPAs was controlled based on the coordinates of that point [21].

3.4 Safety

The irradiation limit of 40 kHz ultrasound (especially for the auditory system) is currently under discussion by different organizations, and no specific value has been determined. We should avoid direct irradiation of high-density ultrasonic waves to the eyes and ears. However, we believe that we can avoid significant safety issues when the proposed method is applied to real environments. First, Nelson et al. mentioned the upper limit for ultrasound exposure to the eyes (17 mW/cm^2) [39], which cannot be exceeded considering the maximum power of the proposed system and the absorption rate of airborne ultrasound into the skin. Second, we can avoid stimulating ears by using fast lip tracking even when users move their faces unexpectedly during the presentation. Third, the lips have high tactile sensitivity, so it is possible to provide notifications with a certain suppression of output intensity. For example, in the experiments explained later, the participants perceived tactile sensation even at one-tenth of the maximum acoustic radiation pressure.

3.5 Lip Conditions

The present study was limited to dry lips. Theoretically, radiation pressure is determined by the acoustic impedance of the target medium [21]. Since skin and water have similar acoustic impedance, a thin layer of water on the lip surface would have little effect on the radiation pressure. However, we should study the tactile changes in wet lips or lips covered with something (lipstick, lip balm) in the future.

Open or moving lips can be less likely to detect tactile presentation because they do not cause multiple reflections like the valley-shaped areas of closed lips. However, since the oral mucosa and tongue are also highly sensitive to touch, we can notice tactile notifications if these areas are stimulated even when the lips are open. In fact, when we presented ultrasonic waves to the oral mucosa and tongue, we could easily detect the sensation.

3.6 Mask

As a result of the pilot study, the lips could feel a weaker tactile sensation when focused ultrasonic waves were presented to lips covered with a mask. This is because a part of the ultrasonic waves passes through the mask. We consider that masks are not a serious problem in this study because the lips can be stimulated even when wearing a mask if the ultrasound irradiation is large enough. Future research should investigate how much the radiation pressure is weakened when a mask is worn. Another way is creating a mask using acoustically transparent materials [8] through which ultrasonic waves can pass.

If the lips are covered by an opaque mask, it is difficult to obtain the position of the lips by image recognition. This problem can be avoided by creating a transparent mask.

3.7 Audible noise

AM is accompanied by audible noise owing to the self-demodulation phenomenon [20]. However, owing to the ultrasonic transducer's directivity and attenuation of ultrasonic waves in the air, the noise is less audible to people who are not in front of the device. In addition, the effective frequency for lip stimulation (e.g., 40 Hz) is near the lower limit of the audible range, making it even harder to hear. In another case, amplitude fluctuations can cause audible noise when the focal point moves quickly, and Suzuki et al. addressed this issue [57]. For these reasons, we do not consider the noise caused by the device to be a severe problem in the proposed method.

4 EXPERIMENT 1: TRANSMISSION OF DIRECTIONAL INFORMATION

In the first experiment, we examined the feasibility of directional information notification using an ultrasonic tactile cue presentation on the lips. Directional information is used in various places in daily life. Directional notifications can indicate the direction people should pay attention to or move towards. Because lips are wide horizontally and convexly curved, we considered that a specific direction could be conveyed intuitively with some accuracy depending on the position where the ultrasonic tactile cue was presented.

We have taken good care to avoid the adverse effects of ultrasound presentation on the human body. Our university's ethical committee approved all experiments with human participants in this study. Participants wore headphones and glasses during the experiments to prevent ultrasonic waves from accidentally damaging their eyes and ears.

4.1 Cue Design

We designed an ultrasonic haptic cue that conveyed directional information. The cue took a total of 900 ms (150 ms presentation followed by 150 ms pause repeated three times). During the presentation, we presented a single stationary focal point of AM 40 Hz at a selected division point. Stimulus intensity was defined as the maximum instantaneous acoustic radiation pressure in a cue. In the experiment, we presented the focal point at the highest stimulus

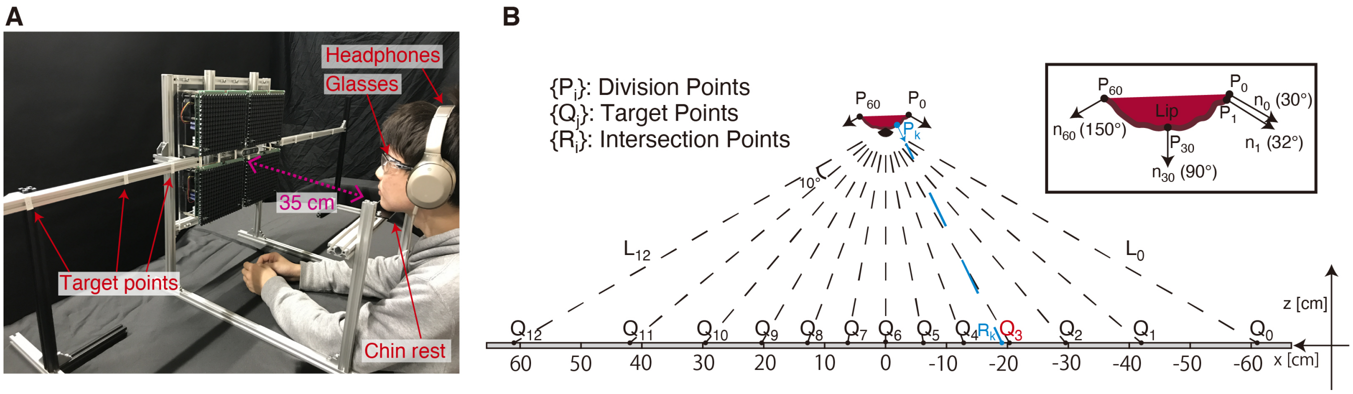

Figure 3: (A) Experimental setup of Experiment 1. (B) Algorithm to determine the presentation position.

intensity ($SI_{\max}$) in the experimental setup. $SI_{\max}$was equivalent to 24.1 mN (2.46gf) in radiation force when measured with an electronic scale (SHINKO DENSHIViBRA AJ II).

We defined the direction conveyed by the cue as the direction normal to the local lip plane where the cue was presented. We automatically determined the division point where the cue was presented using an algorithm that used the coordinates of a target point and all the division points (Fig. 3 (B)). We obtained 61 division points in the experiment. First, we selected a target point ($\vec{Q}_j = (Q_{jx}, 0)^\mathsf{T}$ here). Second, we projected the division points onto the two-dimensional xz-plane and defined a normal ($\vec{n}_i = (n_{ix}, n_{iz})^\mathsf{T}$) corresponding to each division point ($\vec{P}_i = (P_{ix}, P_{iz})^\mathsf{T}$). We assigned a rotation of (30 + 2 × i) degrees to n_i, mapping 120° in front (30–150° from the x-axis) to the division points:

$$\vec{n}_i = \begin{cases} (0, -1)^\mathsf{T} & (i = 30) \\ (1, \tan(30^\circ + 2^\circ \times i))^\mathsf{T} & (i \neq 30) \end{cases} \tag{3}$$

We set the normals in advance because the depth camera failed to get the exact shape of the curve of the lips. Third, we calculated each intersection coordinates ($\{\vec{R}_i = (R_{ix}, 0)^\mathsf{T}\}$) between the x-axis (z = 0) and the vector pointing in the normal direction from each division point:

$$\vec{R}_i = \vec{P}_i + t\vec{n}_i, (t \neq 0) \Rightarrow R_{ix} = P_{ix} - \frac{P_{iz} \times n_{ix}}{n_{iz}} \tag{4}$$

Finally, we chose the division point (P_k here) with the closest intersection to the selected target point (Q_j) as the point where the cue will be presented:

$$k = \arg\min_i |R_{ix} - Q_{jx}| \tag{5}$$

4.2 Experimental setup

Fig. 3 (A) shows the experimental setup. The participants located their lips stationary on a chin rest at 350 mm in the z-direction from the device center. We set the x-axis at the same height as the depth camera and placed 13 target points ($\{\vec{Q}_j = (Q_{jx}, 0)^\mathsf{T}\}$) on the axis (same as Fig. 3 (B)). Each target point had a piece of paper with a number on it. We defined 13 straight lines ($\{L_j\}$) in the range of 120° (30–150°) anterior to the chin rest and assigned a rotation of (30 + 10 × j) degrees to each line. Q_j was placed at the intersection between L_j and the x-axis:

$$Q_{jx} = 350 \times \tan(-60^\circ + 10^\circ \times j) \tag{6}$$

4.3 Procedure

The participants wore glasses and headphones throughout the experiment. Pink noise was continuously played from the headphones to exclude the influence of the driving noise of the AUPAs. The experiment was limited to dry closed lips with nothing on them.

The experimental flow was as follows.

(1) The face was placed stationary on the chin rest.
(2) A target point to be presented next was chosen randomly.
(3) An audio instruction was played 3 seconds before the haptic cue.
(4) The cue (900 ms) was presented to a division point determined by the algorithm described in Section 4.1.
(5) An audio instruction was played to announce the end of the cue.
(6) The participants moved their faces away from the chin rest and faced the direction they thought was presented by the cue.
(7) The participants pointed to a paper in the center of the field of vision.

The above flow was performed 26 times (twice at each target point, in random order) for each participant. Each participant practiced up to two times before entering the main experiment to confirm the experimental procedure. To prevent participants from mapping the division positions to the target points in advance, the number of practices was small enough, and the correct answers were not given.

4.4 Results

Fig. 4 (A) shows a confusion matrix representing the correspondence between the true target points and the answered points. Each cell is expressed as a percentage. Fig. 4 (B) shows a comparison of the root mean square error (RMSE) for each target point. We calculated the RMSE using the angles assigned to each target point

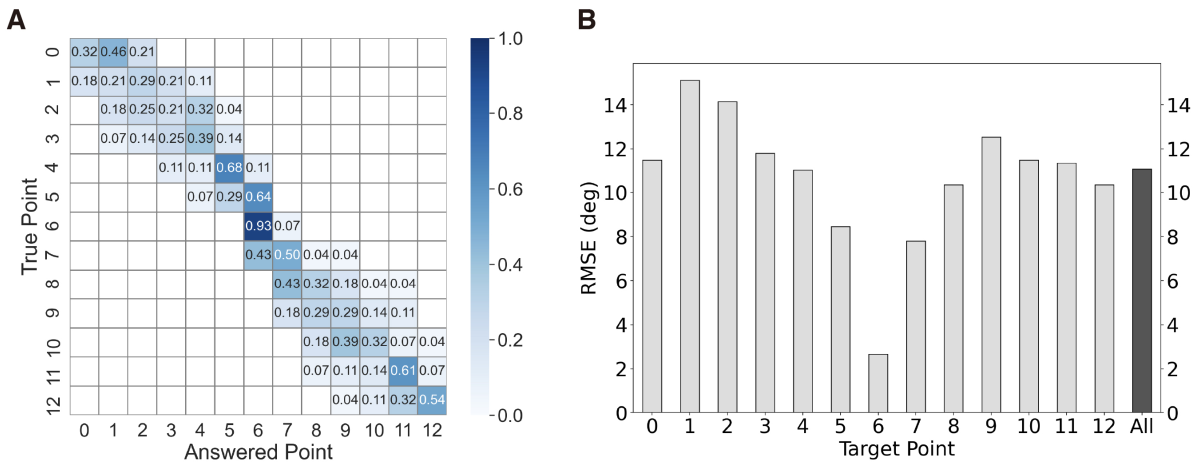

Figure 4: Results of Experiment 1. (A) Confusion matrix between the true target points and the answered points. (B) RMSE for each target point.

(30–150°). A total of 14 participants (2 women and 12 men aged 23–29 years) participated in the experiment. They had experienced ultrasonic tactile presentations to their hands, but rarely to their lips.

As shown in Fig. 4 (A), no participants mistook between the left (0–5) and right directions (7–12). The absolute difference between the true and answered points was 30° or less. The incorrectly answered points tended to be biased inward toward the central target point (6). In Fig. 4 (B), the RMSE for all the target points was approximately 11.1°. For each RMSE, the lowest value was 2.67° (6), and the highest value was 15.1° (1).

4.5 Discussion

We found that our system could transmit directional information with an average accuracy of within ± 11.1°. The Useful Field of View [3] (UFOV, defined as *"the total visual field area in which useful information can be acquired without eye and head movements"*) was found to be the area between 20° and 30° in front, although it varied depending on the task. Considering the UFOV, the true direction conveyed by the ultrasonic cue was approximately within the UFOV when facing the answered direction. Therefore, we can say that the algorithm used in this study conveyed directional information with sufficient accuracy in the 120° range in front, and without the need for prior mapping between the presentation positions and angles.

The bias of the incorrectly answered points toward the center point occurs probably because the angle of the pre-assigned normals for each division point was inappropriate. In the future, we can consider creating a mapping model between the presentation position of the cue and the direction answered by the participants.

5 EXPERIMENT 2: ASSESSMENT OF AFFECTIVE RESPONSES

In the second experiment, we investigated the effect of different ultrasonic haptic cues on the lips on the affective responses. Emotion is important information that influences people's behavior. Tactile sensations play an essential role in the transmission of emotions [10]. We considered investigating whether ultrasonic tactile presentation to the lips would change the evoked emotion.

We used the 9-point Self-Assessment Manikin (SAM) [6] to assess affective responses in terms of valence and arousal. Valence is a measure of the pleasantness of a stimulus, ranging from 1 (unpleasant) to 9 (pleasant). Arousal is a measure of the intensity of emotion provoked by a stimulus, ranging from 1 (calm) to 9 (excited).

5.1 Cue Design

We designed 12 ultrasonic haptic cues (two stimulus intensities × six spatiotemporal patterns). We determined these two parameters mainly based on previous studies regarding affective touch [41, 63]. All cues were 2 seconds long and presented a single focal point of AM 40 Hz. The spatiotemporal pattern represents how the focal point moved for 2 seconds.

Two stimulus intensities were used: $SI_{\max}$and SI_{th}. If $SI_{\max}$is defined as 0 dB, then $SI_{\text{th}}$is the stimulus intensity corresponding to approximately -20.1 dB. We confirmed in a pilot study that $SI_{\text{th}}$was perceived but was much weaker than $SI_{\max}$. We prepared two significantly different intensity conditions mainly by referring to [63]. In [63], low intensity stimuli were perceived as more pleasant, and high intensity stimuli more arousing. As for valence, it was similarly described in [41].

Fig. 5 (A) shows six spatiotemporal patterns. We obtained 81 division points in the experiment. STP_0 and STP_1 are both stationary patterns for 2 seconds. Respectively, the focal point stays at the left commissure (P_0) and the center (P_{40}). STP_2 and STP_3 are patterns that reciprocate four times in 2 seconds through a quarter of the total division points. STP_2 moves between P_0 and P_{20}, and STP_3 between P_{30} and P_{50}. STP_4 and STP_5 reciprocate through all the division points (between P_0 and P_{80}) in 2 seconds. During the presentation, STP_4 reciprocates once and STP_5 four times. Regarding the spatial movement pattern, we slightly referred to [41]. We prepared patterns to compare the center of the lips (STP_1, STP_3)

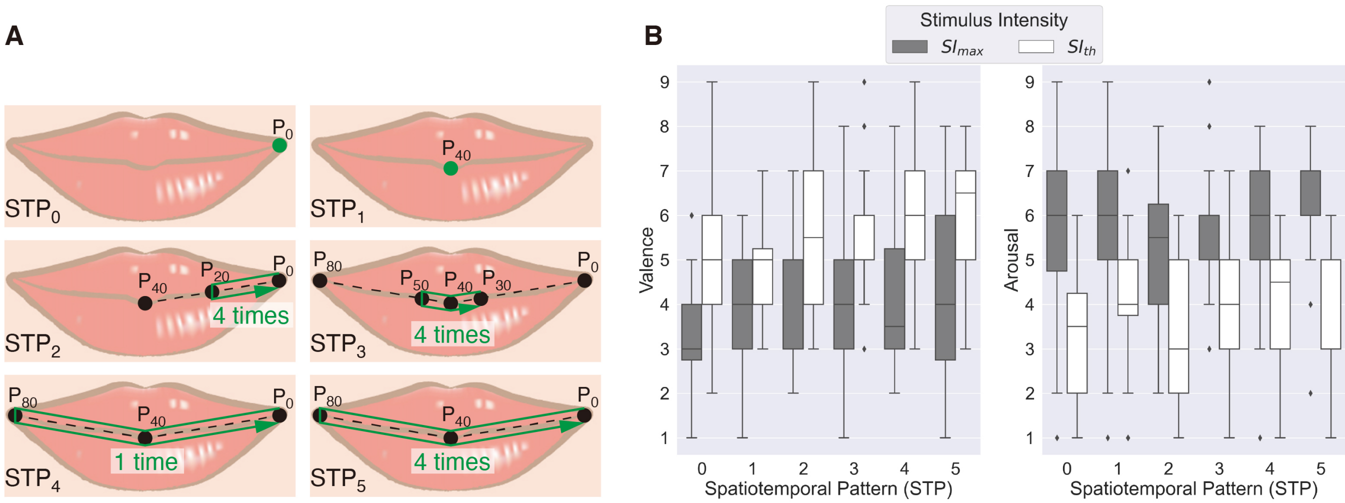

Figure 5: Results of Experiment 2. (A) Six spatiotemporal patterns. (B) Evaluation of valence and arousal for each cue.

with the edge of the lips (STP_0, STP_2) since some people in the pilot study indicated that the presentation to the edge was more unpleasant than to the center. As for the movement speed, we referred to [63]. C-tactile (CT) afferents in the hairy skin are said to have the potential to elicit pleasant perceptions [63]. CT afferents in the forearms responded most vigorously at 1–10 cm/s when using a soft brush, and subjects perceived the stimulus as most pleasant [35]. Tsalamlal et al. suggested that similar results could be obtained for non-contact tactile stimulation of the forearms using air jets [63]. Though lips are hairless and have no CT afferents, we prepared patterns for static (STP_0, STP_1), slow movement (STP_4), and fast movement (STP_5). Assuming that the width of the lips is about 5 cm, STP_4 and STP_5 respectively correspond to about 5 cm/s and 20 cm/s.

5.2 Procedure

The experimental setup was the same as in Experiment 1, but there was a paper with images of SAM manikins under the AUPAs. There were no objects in the participants' field of view that significantly affected valence or arousal.

The experimental flow was as follows.

(1) The face was placed stationary on the chin rest.
(2) A cue to be presented next was chosen randomly.
(3) An audio instruction was played 3 seconds before the haptic cue.
(4) The cue (2 s) was presented.
(5) An audio instruction was played to announce the end of the cue.
(6) The participants evaluated valence and arousal, pointing to the corresponding values (1–9).

The above flow was performed 24 times (twice at each cue, in random order) for each participant.

5.3 Results

Fig. 5 (B) shows the evaluation of the valence and arousal for each cue. The participants were the same as in Experiment 1. The Shapiro-Wilk test showed that most of the data sets did not follow a normal distribution (valence: 10/12, arousal: 8/12), so we performed non-parametric tests.

The effect of the stimulus intensity was remarkable. In all the spatiotemporal patterns, the Wilcoxon signed-rank test showed a significant difference between $SI_{\mathrm{max}}$and SI_{th}in both valence and arousal ($p < 0.05$). On the other hand, the spatiotemporal pattern did not significantly affect the affective responses. In both the stimulus intensities, the Friedman test showed that the six spatiotemporal patterns were not significantly different in valence or arousal ($p \geq 0.05$).

5.4 Discussion

We found that the stimulus intensity mainly determined the affective responses in ultrasonic haptic cues on the lips. Overall, the stronger stimuli (SI_{max}) elicited more unpleasant and more excited emotions, while the weaker stimuli (SI_{th}) elicited more pleasant and calmer emotions. This result was similar to the previous studies [10, 41, 63]. On the other hand, it was difficult to evoke pleasant emotions with high arousal, as well as unpleasant ones with low arousal. This polarization could be caused by two factors. First, the used stimulus intensities were at the extremes (SI_{max}: highest stimulus intensity using AUPAs, SI_{th}: near the tactile threshold of the lips), and there was no intermediate intensity. Second, the lips are less exposed to strong tactile sensations, so the participants might feel unpleasant and excited if they experienced even a slightly strong stimulus.

No significant differences for spatiotemporal patterns were found. Several participants stated that stimulation to the edge was more unpleasant than to the center, but there was no significant difference overall in terms of location. As for the movement speed, it is probably due to the lack of CT afferents. Löken et al. suggested that

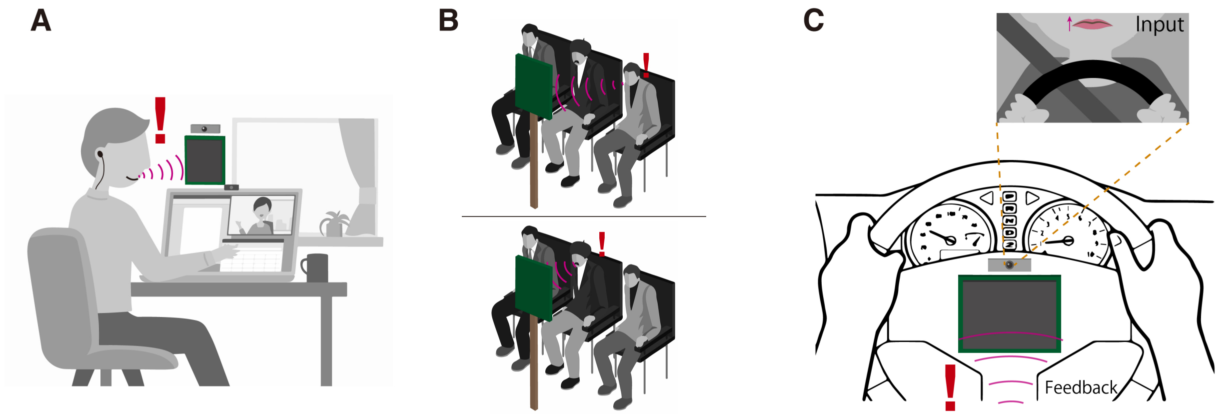

Figure 6: Three applications. (A) Notifications During Work, (B) Calling in the Waiting Room, (C) Tactile Feedback in Automotive User Interfaces

in the palms, which lack CT afferents, no relationship was found between brush velocity and pleasantness ratings [35].

We concluded that we could elicit sufficient changes in affective responses for the applications shown in Section 6.3. If we want to convey important or urgent information, we had better present a cue at $SI_{\max}$. If not, it is better to present the cue at SI_{th}.

6 GENERAL DISCUSSION

The experimental results showed that the ultrasonic tactile presentation to the lips had sufficient performance in transmitting directional information and eliciting affective responses. In this section, we discuss the proposed method from a more practical perspective.

6.1 Combination of Cues

We used a single cue for each presentation in the experiments, but we can also combine the directional and emotional cues into a single cue. Experiment 2 indicated that we could evoke different affective responses regardless of the presentation position. This suggests that we can independently convey directional and emotional information to the lips. For example, if a directional cue is presented at $SI_{\max}$, it can tell the users that there is something important or dangerous in that direction.

6.2 Limitation

We should improve the effective presentation distance (approximately 40 cm in the current system) to use it for a broader range of applications. Airborne ultrasound tactile presentation at long distances is an area that is currently being actively researched. Hasegawa et al. [18] and Suzuki et al. [59] achieved ultrasonic tactile presentation at a distance of 1 m using multiunit AUPAs. Ariga et al. showed that 20cm-square AUPAs could create a 20cm-cube workspace, where an ultrasonic focal point could be formed, at a distance of 1.6m [28]. Currently, it is costly to create AUPAs capable of ultrasound presentation at long distances. However, if research on this topic continues to develop, various applications using non-contact tactile notifications over long distances will emerge.

Another issue is the bulkiness of AUPAs. If the current AUPAs are placed in front of the face to stimulate the lips, they may interfere with the work area. Kamigaki et al. proposed a thin and flexible AUPA using electrostatic force-driven ultrasound transducers [27]. As the devices become thin, they can get easier to place in the human environment.

6.3 Specific Applications

The proposed method opens a new and useful interaction; the non-contact tactile notification using the lips. Our system can be applied for various purposes in daily life. Fig. 6 shows specific applications. As discussed in Section 2.4, we note that the proposed method does not require users to wear or bring anything in advance.

6.3.1 Notifications During Work. Various distractions can occur during a remote meeting, such as visitors, notifications of the following schedules. Users do not want to suddenly take their eyes or ears off the meeting not to miss important information. Therefore, notifications using the display on the screen or voice over the earphones may be unsuitable in this case.

The proposed method allows the users to receive notifications while keeping their eyes and ears focused on the meeting (Fig. 6 (A)). By linking the proposed method with a calendar application or home appliance system, the user can be notified at the right timing. The stimulus intensity can convey the importance of notified information. For less urgent notifications (e.g., 30 min before the next meeting), a calm cue (at SI_{th}) is fine. On the other hand, if there is an important notification (e.g., visitors), an exciting cue (at $SI_{\max}$) would be better. As mentioned in Section 6.1, a combination of cues is useful here. When important visitors come to visit, directional cues at $SI_{\max}$could be used to draw the user's attention in the direction of the intercom.

6.3.2 Calling in the Waiting Room. In hospitals, we often wait for our turn in the waiting room. Sometimes we must wait for a long time without doing anything in order not to miss our waiting number displayed or called.

The proposed method can be an effective alternative to other calling methods (Fig. 6 (B)). As long as the users' lips are exposed, they can perform different activities during the waiting time, such as watching videos, listening to music, or reading books with their hands. Another advantage of the proposed method is that it can form an ultrasonic focal point at any three-dimensional position in a specific range by controlling the transducers' phases. By combining the proposed method with face recognition, a single device could notify multiple people within the effective presentation distance (described in Section 6.2) in the waiting order.

6.3.3 Tactile Feedback in Automotive User Interfaces. The combination of hand gestures and ultrasonic haptic feedback has received much attention as an effective interaction in automotive user interfaces [13, 17, 52]. It is considered to have several advantages over touchscreens and audio input/feedback systems: it allows drivers to keep their eyes on roads and is not affected by external auditory noise. However, past studies assume that the drivers take one hand off the wheel to receive haptic feedback while driving, which can still lead to accidents.

One possible way to perform in-vehicle interactions while keeping the hands on the wheel is to use the lips as a user interface (Fig. 6 (C)). We can consider combining lip gesture recognition via image tracking [9] (input) with LipNotif (feedback). As examples of inputs, users can move their lips left or right to select songs in the car, or move them up or down to adjust the temperature of the air conditioner. Tactile feedback can be presented to the lips as a confirmation of the input. For another use, in combination with drowsiness detection algorithms [12, 64], the system can alert the drowsy drivers.

6.4 Future Work

This research leads to different future studies related to notifications using ultrasonic tactile presentation to the lips. First, we should explore the possibility of using a more complex cue to provide detailed information notifications. In addition to the cues used in this study, different cues can be designed using multiple ultrasonic focal points, other modulation types (Lateral Modulation [60, 61] or Spatiotemporal Modulation [11]), complex rhythms, continuous changes in stimulus intensity, and combination with other modalities (auditory or visual feedback). Simultaneously, we should investigate whether the lips can distinguish between these cues.

We should also consider presenting non-contact tactile sensations to the lips from various angles. In the experiments, we focused on the case where the device was placed directly in front of the face. However, when introducing the device into a real-world environment, the device can be placed obliquely to the face. Jingu et al. [26] suggested that even when the device is placed at an angle to the face, presenting the focal point in a valley-shaped region horizontal to the device plane can cause multiple reflections of ultrasonic waves, which results in a stronger tactile sensation. For detecting profile faces in images, OpenFace [4] is more suitable than Dlib.

Besides the masks (Section 3.6), no obstacles are desirable between the lips and the device. We may be able to overcome this limitation by using self-bending ultrasound beams [40].

7 CONCLUSION

We proposed LipNotif, a non-contact tactile notification system that uses airborne ultrasound tactile presentation to lips. Lips are suitable for non-contact tactile notifications because they have high tactile sensitivity comparable to the palms, are less occupied in daily life, and are constantly exposed outward. We developed a notification system that automatically recognizes the position of the lips and presents non-contact tactile sensations. To the best of our knowledge, this study is the first to consider the use of lips in non-contact haptic cues. In the first experiment, we found that the directional information can be notified to the lips with an average accuracy of ± 11.1° in the 120° horizontal range. In the second experiment, we could elicit significantly different affective responses by changing the stimulus intensity. The experimental results indicated that the proposed method is practical for conveying directions, emotions, and combinations of them.

This research opens up a new interaction: non-contact tactile notifications using only lips, without sight, hearing, or hands. Our system can be applied for various purposes, such as notifications during work, calling in the waiting room, and tactile feedback in automotive user interfaces.

REFERENCES

[1] Tomohiro Amemiya and Hisashi Sugiyama. 2009. Navigation in Eight Cardinal Directions with Pseudo-Attraction Force for the Visually Impaired. In *2009 IEEE International Conference on Systems, Man and Cybernetics*. IEEE, 27–32.

[2] Kentaro Ariga, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2020. Midair Haptic Presentation Using Concave Reflector. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 307–315.

[3] Karlene K Ball, Bettina L Beard, Daniel L Roenker, Richard L Miller, and David S Griggs. 1988. Age and visual search: Expanding the useful field of view. *JOSA A* 5, 12 (1988), 2210–2219.

[4] Tadas Baltrusaitis, Amir Zadeh, Yao Chong Lim, and Louis-Philippe Morency. 2018. OpenFace 2.0: Facial Behavior Analysis Toolkit. In *2018 13th IEEE International Conference on Automatic Face & Gesture Recognition (FG 2018)*. IEEE, 59–66.

[5] Steven M Barlow. 1987. Mechanical Frequency Detection Thresholds in the Human Face. *Experimental neurology* 96, 2 (1987), 253–261.

[6] Margaret M Bradley and Peter J Lang. 1994. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry* 25, 1 (1994), 49–59.

[7] Stephen A Brewster and Lorna M Brown. 2004. Tactons: Structured Tactile Messages for Non-Visual Information Display. (2004).

[8] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. 505–514.

[9] Piotr Dalka and Andrzej Czyzewski. 2010. Human-Computer Interface Based on Visual Lip Movement and Gesture Recognition. *Int. J. Comput. Sci. Appl.* 7, 3 (2010), 124–139.

[10] Mohamad A Eid and Hussein Al Osman. 2015. Affective Haptics: Current Research and Future Directions. *IEEE Access* 4 (2015), 26–40.

[11] William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. 2018. Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-air. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 270–281.

[12] Jay D Fuletra and Dulari Bosamiya. 2013. A Survey on Drivers Drowsiness Detection Techniques. *International Journal on Recent and Innovation Trends in Computing and Communication* 1, 11 (2013), 816–819.

[13] Orestis Georgiou, Valerio Biscione, Adam Harwood, Daniel Griffiths, Marcello Giordano, Ben Long, and Tom Carter. 2017. Haptic In-Vehicle Gesture Controls. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*. 233–238.

[14] Hyunjae Gil, Hyungki Son, Jin Ryong Kim, and Ian Oakley. 2018. Whiskers: Exploring the Use of Ultrasonic Haptic Cues on the Face. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.

[15] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. 2017. HapticClench: Investigating Squeeze Sensations Using Memory Alloys. In *Proceedings*

of the 30th Annual ACM Symposium on User Interface Software and Technology. 109–117.

[16] Sidhant Gupta, Dan Morris, Shwetak N Patel, and Desney Tan. 2013. AirWave: Non-Contact Haptic Feedback Using Air Vortex Rings. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing.* 419–428.

[17] Kyle Harrington, David R Large, Gary Burnett, and Orestis Georgiou. 2018. Exploring the Use of Mid-Air Ultrasonic Feedback to Enhance Automotive User Interfaces. In *Proceedings of the 10th international conference on automotive user interfaces and interactive vehicular applications.* 11–20.

[18] Keisuke Hasegawa and Hiroyuki Shinoda. 2018. Aerial Vibrotactile Display Based on Multiunit Ultrasound Phased Array. *IEEE Transactions on Haptics* 11, 3 (2018), 367–377.

[19] Yuki Hashimoto, Naohisa Nagaya, Minoru Kojima, Satoru Miyajima, Junichiro Ohtaki, Akio Yamamoto, Tomoyasu Mitani, and Masahiko Inami. 2006. Straw-like User Interface: Virtual experience of the sensation of drinking using a straw. In *Proceedings of the 2006 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology.* 50–es.

[20] Takayuki Hoshi. 2017. Noise Reduction of Airborne Ultrasound Tactile Display on Moving Stimulation Point. In *Trans. Virtual Reality Soc. Japan*, Vol. 22. 293–300.

[21] Takayuki Hoshi, Masafumi Takahashi, Takayuki Iwamoto, and Hiroyuki Shinoda. 2010. Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound. *IEEE Transactions on Haptics* 3, 3 (2010), 155–165.

[22] Alexandra Ion, Edward Jay Wang, and Patrick Baudisch. 2015. Skin Drag Displays: Dragging a Physical Tactor across the User's Skin Produces a Stronger Tactile Stimulus than Vibrotactile. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* 2501–2504.

[23] Takayuki Iwamoto, Mari Tatezono, and Hiroyuki Shinoda. 2008. Non-contact Method for Producing Tactile Sensation Using Airborne Ultrasound. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications.* Springer, 504–513.

[24] Seungwoo Je, Minkyeong Lee, Yoonji Kim, Liwei Chan, Xing-Dong Yang, and Andrea Bianchi. 2018. PokeRing: Notifications by Poking Around the Finger. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.* 1–10.

[25] Seungwoo Je, Brendan Rooney, Liwei Chan, and Andrea Bianchi. 2017. tactoRing: A Skin-Drag Discrete Display. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* 3106–3114.

[26] Arata Jingu, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shionda. 2021. Tactile Perception Characteristics of Lips Stimulated by Airborne Ultrasound. In *2021 IEEE World Haptics Conference (WHC).*

[27] Takaaki Kamigaki, Akihito Noda, and Hiroyuki Shinoda. 2017. Thin and Flexible Airborne Ultrasound Phased Array for Tactile Display. In *2017 56th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE).* IEEE, 736–739.

[28] Ariga Kentaro, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shionda. 2021. Workspace Evaluation of Long-Distance Midair Haptic Display Using Curved Reflector. In *2021 IEEE World Haptics Conference (WHC).*

[29] Davis E. King. 2009. Dlib-ml: A Machine Learning Toolkit. *Journal of Machine Learning Research* 10 (2009), 1755–1758.

[30] Hojin Lee, Ji-Sun Kim, Seungmoon Choi, Jae-Hoon Jun, Jong-Rak Park, A-Hee Kim, Han-Byeol Oh, Hyung-Sik Kim, and Soon-Cheol Chung. 2015. Mid-Air Tactile Stimulation Using Laser-Induced Thermoelastic Effects: The First Study for Indirect Radiation. In *2015 IEEE World Haptics Conference (WHC).* IEEE, 374–380.

[31] Jaeyeon Lee and Geehyuk Lee. 2016. Designing a Non-contact Wearable Tactile Display Using Airflows. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology.* 183–194.

[32] Minkyeong Lee, Seungwoo Je, Woojin Lee, Daniel Ashbrook, and Andrea Bianchi. 2019. ActivEarring: Spatiotemporal Haptic Cues on the Ears. *IEEE Transactions on Haptics* 12, 4 (2019), 554–562.

[33] Seungyon" Claire" Lee and Thad Starner. 2010. BuzzWear: Alert Perception in Wearable Tactile Displays on the Wrist. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* 433–442.

[34] Wei Liu and Hui Tang. 2005. An initial study on lip perception of electrotactile array stimulation. *Journal of Rehabilitation Research & Development* 42, 5 (2005).

[35] Line S Löken, Johan Wessberg, Francis McGlone, and Håkan Olausson. 2009. Coding of pleasant touch by unmyelinated afferents in humans. *Nature neuroscience* 12, 5 (2009), 547–548.

[36] Flavia Mancini, Armando Bauleo, Jonathan Cole, Fausta Lui, Carlo A Porro, Patrick Haggard, and Gian Domenico Iannetti. 2014. Whole-Body Mapping of Spatial Acuity for Pain and Touch. *Annals of neurology* 75, 6 (2014), 917–924.

[37] Saya Mizutani, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2019. Thresholds of Haptic and Auditory Perception in Midair Facial Stimulation. In *2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE).* IEEE, 1–6.

[38] Yasuaki Monnai, Keisuke Hasegawa, Masahiro Fujiwara, Kazuma Yoshino, Seki Inoue, and Hiroyuki Shinoda. 2014. HaptoMime: Mid-Air Haptic Interaction with a Floating Virtual Screen. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology.* 663–667.

[39] Thomas R Nelson, J Brian Fowlkes, Jacques S Abramowicz, and Charles C Church. 2009. Ultrasound Biosafety Considerations for the Practicing Sonographer and Sonologist. (2009).

[40] Mohd Adili Norasikin, Diego Martinez Plasencia, Spyros Polychronopoulos, Gianluca Memoli, Yutaka Tokuda, and Sriram Subramanian. 2018. SoundBender: Dynamic Acoustic Control Behind Obstacles. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology.* 247–259.

[41] Marianna Obrist, Sriram Subramanian, Elia Gatti, Benjamin Long, and Thomas Carter. 2015. Emotions Mediated Through Mid-Air Haptics. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* 2053–2062.

[42] Viktorija Paneva, Sofia Seinfeld, Michael Kraiczi, and Jörg Müller. 2020. *HaptiRead: Reading Braille as Mid-Air Haptic Information.* Association for Computing Machinery, New York, NY, USA, 13–20. https://doi.org/10.1145/3357236.3395515

[43] Roshan Lalitha Peiris, Yuan-Ling Feng, Liwei Chan, and Kouta Minamizawa. 2019. ThermalBracelet: Exploring Thermal Haptic Feedback Around the Wrist. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* 1–11.

[44] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017. Squeezeback: Pneumatic Compression for Notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* 5318–5330.

[45] Ismo Rakkolainen, Euan Freeman, Antti Sand, Roope Raisamo, and Stephen Brewster. 2020. A Survey of Mid-Air Ultrasound Haptics and Its Applications. *IEEE Transactions on Haptics* (2020).

[46] Nimesha Ranasinghe, Pravar Jain, Shienny Karwita, David Tolley, and Ellen Yi-Luen Do. 2017. Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* 1731–1742.

[47] Nimesha Ranasinghe, Pravar Jain, Nguyen Thi Ngoc Tram, Koon Chuan Raymond Koh, David Tolley, Shienny Karwita, Lin Lien-Ya, Yan Liangkun, Kala Shamaiah, Chow Eason Wai Tung, et al. 2018. Season Traveller: Multisensory Narration for Enhancing the Virtual Reality Experience. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.* 1–13.

[48] Thijs Roumen, Simon T Perrault, and Shengdong Zhao. 2015. NotiRing: A Comparative Study of Notification Channels for Wearable Interactive Rings. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* 2497–2500.

[49] Hooman Aghaebrahimi Samani, Rahul Parsani, Lenis Tejada Rodriguez, Elham Saadatian, Kumudu Harshadeva Dissanayake, and Adrian David Cheok. 2012. Kissenger: Design of a Kiss Transmission Device. In *Proceedings of the Designing Interactive Systems Conference.* 48–57.

[50] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-Mounted Display with Mid-Air Tactile Feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology.* 51–58.

[51] Antti Sand, Ismo Rakkolainen, Veikko Surakka, Roope Raisamo, and Stephen Brewster. 2020. Evaluating Ultrasonic Tactile Feedback Stimuli. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications.* Springer, 253–261.

[52] Gözel Shakeri, John H Williamson, and Stephen Brewster. 2018. May the Force Be With You: Ultrasound Haptic Feedback for Mid-Air Gesture Interaction in Cars. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* 1–10.

[53] Maria Z Siemionow, Bahar Bassiri Gharb, and Antonio Rampazzo. 2011. The Face as a Sensory Organ. In *The Know-How of Face Transplantation.* Springer, 11–23.

[54] Rajinder Sodhi, Ivan Poupyrev, Matthew Glisson, and Ali Israr. 2013. AIREAL: Interactive Tactile Experiences in Free Air. *ACM Transactions on Graphics (TOG)* 32, 4 (2013), 1–10.

[55] Sunghyun Song, Geeyoung Noh, Junwoo Yoo, Ian Oakley, Jundong Cho, and Andrea Bianchi. 2015. Hot & Tight: Exploring Thermo and Squeeze Cues Recognition on Wrist Wearables. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers.* 39–42.

[56] Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. 2017. Sparkle: Hover Feedback with Touchable Electric Arcs. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* 3705–3717.

[57] Shun Suzuki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2020. Reducing Amplitude Fluctuation by Gradual Phase Shift in Midair Ultrasound Haptics. *IEEE Transactions on Haptics* 13, 1 (2020), 87–93.

[58] Shun Suzuki, Seki Inoue, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2021. AUTD3: Scalable Airborne Ultrasound Tactile Display. *IEEE Transactions on Haptics* (2021).

[59] Shun Suzuki, Ryoko Takahashi, Mitsuru Nakajima, Keisuke Hasegawa, Yasutoshi Makino, and Hiroyuki Shinoda. 2018. Midair haptic display to human upper body. In *2018 57th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE).* IEEE, 848–853.

[60] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. 2018. Lateral Modulation of Midair Ultrasound Focus for Intensified Vibrotactile Stimuli. In

International Conference on Human Haptic Sensing and Touch Enabled Computer Applications. Springer, 276–288.

[61] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. 2020. Tactile Stimulation by Repetitive Lateral Movement of Midair Ultrasound Focus. *IEEE Transactions on Haptics* 13, 2 (2020), 334–342.

[62] Mats Trulsson and Greg K Essick. 2010. Sensations Evoked by Microstimulation of Single Mechanoreceptive Afferents Innervating the Human Face and Mouth. *Journal of neurophysiology* 103, 4 (2010), 1741–1747.

[63] Mohamed Yassine Tsalamlal, Nizar Ouarti, Jean-Claude Martin, and Mehdi Ammi. 2013. EmotionAir: Perception of Emotions from Air Jet Based Tactile Stimulation. In *2013 Humaine Association Conference on Affective Computing and Intelligent Interaction*. IEEE, 215–220.

[64] Hiroshi Ueno, Masayuki Kaneda, and Masataka Tsukino. 1994. Development of Drowsiness Detection System. In *Proceedings of VNIS'94-1994 Vehicle Navigation and Information Systems Conference*. IEEE, 15–20.

[65] Yunqing Wang and Katherine J Kuchenbecker. 2012. HALO: Haptic Alerts for Low-hanging Obstacles in White Cane Navigation. In *2012 IEEE Haptics Symposium (HAPTICS)*. IEEE, 527–532.

[66] Sidney Weinstein. 1968. Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex and Laterality. *The skin senses* (1968).

[67] Alexander Wilberz, Dominik Leschtschow, Christina Trepkowski, Jens Maiero, Ernst Kruijff, and Bernhard Riecke. 2020. FaceHaptics: Robot Arm based Versatile Facial Haptics for Immersive Environments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.