

# Representation of Humidity Change Based on Heating the Local Skin

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## Abstract

Humidity is one of the major components to represent an ambient environment. Humid sensations affect comfort. Warm and dry wind when walking outside is comfortable, while hot and humid environments are uncomfortable. It would be preferable that a humid sensation display is able to induce sensations by presenting stimuli only to the local skin, not to the whole skin for compactness of the device size. The aim of this study is to enhance humid sensations with presenting stimuli only to the local skin, whose skin area is 60 mm square. We propose a method to display humid sensations by LED light heating to generate high humid air close to the skin. We also propose a time-division presentation for humid sensations. The developed device equips LED light heating components in addition to both mist and dry air generators. The results of the subjective study confirmed the effectiveness of LED light heating in increase the humid sensations. The results also suggested that a time-division presentation reduced variability in the induction of sensations. The proposed method enabled to induce the humid sensations efficiently with the limited device size.

## CCS Concepts

• **Human-centered computing** → **Interaction devices**; • **Hardware** → **Haptic devices**;

## 1. Introduction

Humidity is one of the most important components of ambient air properties and conditions that affect human comfort [ARVA23]. Warm and dry wind when walking outside is comfortable, while hot and humid environments are uncomfortable. In a virtual reality (VR) experience, the representation of humidity is important to create a realistic sense of ambient air. The sense of humidity in reality is felt in situations where moist air surrounds a large area of the human body. However, presenting stimuli to the entire body requires a large presentation device and takes time to replace the stimulus. It would be preferable that a humid sensation display is able to induce sensations by presenting stimuli only to the local skin e.g. hand, cheek, or neck, not to the whole skin for compactness of the device size.

The aim of this study is to enhance humid sensations with presenting stimuli only to the local skin. For this purpose, humid air should be placed as close to the skin as possible to induce the humid sensation efficiently. Therefore, we propose a method to display humid sensations by evaporating skin moisture and generating high humid air close to the skin with LEDs, as shown in Fig. 1(a)(b). We also propose a time-division humid presentation method, as shown

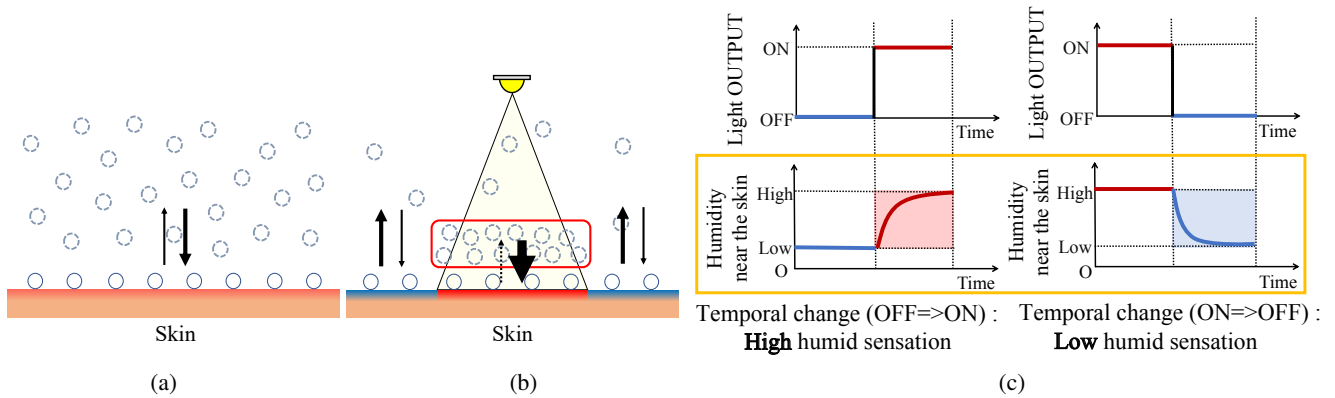
in Fig. 1(c), because it is known that the human senses are sensitive to change [MGD77]. The contributions of this study are

- We propose a novel method to display humid sensations by heating with LEDs.
- We also propose a time-division humid presentation method.
- We investigate the effects of LED light heating and time-division presentation on increasing humid sensations.

## 2. Related Works

To express conditions of ambient air, some studies focused on representing coldness or hotness of the air. Han et al. proposed a method of presenting coldness or hotness using a mist generator and a ceramic lamp [HCL\*18]. When the mist on the skin evaporates, heat is lost from the skin. This cools down the skin. Nakajima et al. provided pinpoint cold stimulation by accelerating the vaporization of mist applied to human skin with focused ultrasound [NHMS21]. Xu et al. delivered cold air generated instantaneously by the vortex effect to human skin [XYIK22]. In this case, the heat transfers from the human skin to the delivered cold air.

As for studies on humidity sensory presentation, studies have been conducted mainly on the wetness of objects. Shibahara et al. investigated the wetness of a cloth by varying the temperature



**Figure 1:** Methods of inducing the humid sensations: (a) real-life humid stimuli to the *WHOLE* skin, (b) proposed method by heating the *LOCAL* skin to generate humid air close to the skin with LEDs, (c) time-division humid presentation method: LED light is switched from OFF to ON or from ON to OFF to increase/decrease humidity near the skin, respectively.

and moisture content of the cloth and the method of contact when touching the cloth, and reported that they perceived an illusion of wetness from a dry, cold cloth [SS19]. It was suggested that the decrease in skin temperature that occurs when touching a wet object causes the illusion of wetness. Peiris et al. presented the sensation of wetness with a head-mounted display that integrated thermal and vibrotactile sensation [PCM18].

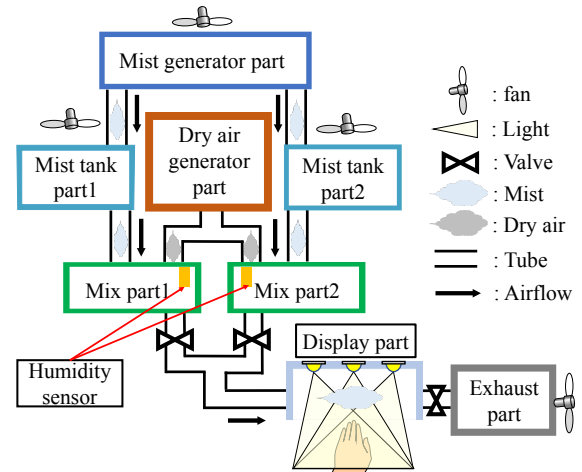
As for multi-sensory studies, Chen et al. presented midair olfactory system [CHL\*18]. Hülsmann et al. developed a system for creating wind and warmth simulations [HFWM14]. Ranasinghe et al. enhanced sensory engagement within interactive experiences by using olfactory and haptic (thermal and wind) stimuli [RJTNT\*18].

In a study of presenting air humidity, Hokoyama et al. considered that the main factor of humidity sensation is the presence of water droplets on the skin surface without evaporation, and reported that higher humidity in a chamber is perceived as warmer by a hand placed in the chamber [HKK\*17]. Similarly, some studies reported that high humidity makes the warm or hot sensation stronger in a warm/hot environment [ARVA23, Ber97]. However, the plausible mechanism underlying humid sensations caused by air humidity are still unrevealed [WSSN24]. Watanabe et al. described that in a hot environment, sweating accelerates thermoregulation by promoting heat loss based on evaporation from skin surface; however, high humidity suppresses the process of this acceleration [WSSN24]. This suppression by the humid air could be involved with humid sensation. By extending Hokoyama's and Watanabe's considerations, the suppression of evaporation will be enhanced by heating local skin, which has moisture inside, and generating humid air close to skin.

### 3. Proposed Method

#### 3.1. Concept

In this study, we propose a method to present humid sensation by changing the humidity state near the skin due to light heating, as shown in Fig. 1(b). We also clarify the effect of changing the



**Figure 2:** Schematic of prototype system: two mist tank parts are prepared to test the time-division presentation of the mist transportation in addition to LED light heating.

humidity conditions over time on the humid sensation. Fig. 1(c) shows the time-division humid presentation method. LED light is switched from OFF to ON to increase humidity, while LED light is switched from ON to OFF to decrease humidity near the skin. The temporal change instead of the steady state would enhance the induction of the humid sensation by suppressing the receptor's adaptation.

#### 3.2. Configuration of the Proposed System

Compared to a conventional method of delivering mist to the skin, such as Hokoyama's work [HKK\*17], the system consists of a mist generator, a dry air generator, two mist tank parts, two mix parts, a display part with LEDs, and a discharge part, as shown in Fig. 2. We prepared two mist tank parts because we test the time-division pre-

sensation of the mist transportation in addition to LED light heating. For example, high humidity air is transported after low humidity air is transported. In the mist generator, an ultrasound transducer (SEIKO GIKEN INC., IM6-36D/S) generates mist, and a DC fan (SANYO DENKI CO., LTD., SanAce 60W) installed in the mist generator conveys the mist through a tube to the two mist tank parts. The mist tank part stores the mist transported from the mist generator part and transports the mist to the mix part using a DC fan (SanAce 40W, Sanyo Electric Co., Ltd.) installed in the mist tank part. In the dry air generator part, a dry air generator (N-Tech, SCU-30C: 20 L/min air with a low dew point of  $-20^{\circ}\text{C}$ ) conveys dry air to the two mix parts. In the mix part, the mist transported by the mist tank part and the dry air transported by the dry air generator part are mixed, and the output of the DC fan in the mist tank part is controlled by the value of the temperature and humidity sensor (Sensirion, SHT85) installed in the mix part. The amount of mist transported from the mist tank part is controlled by controlling the output of the DC fan in the mist tank part according to the value of the temperature and humidity sensor installed in the mist tank part. The air with the desired humidity is then transported to the display part where stimuli are presented to the skin. The exhaust part is designed to ventilate the air from the display part.

The developed humid sensation presentation device is shown in Fig. 3. The mist generator part has an ultrasound transducer and water in a tank. When the ultrasound transducer is activated, mist of 4800 ml/h is generated and transported by a DC fan installed in the mist generator part to the mist tank parts. The mix parts are connected by tubing to the mist tank parts, the dry air generation part, and the display part. A valve that can be opened and closed by a servo motor (Tower Pro Pte Ltd, SG-90) turns on and off the supply of air with the desired humidity to the display part.

The display part consists of LEDs for light heating and a humidity display part, as shown in Fig. 4. The display part consists of 12 cool white LEDs (CREE XPGWHT-L1-STAR-G53 5W) with a heat sink and a lens (CREE LL01CR-DF40L06-M2-T,  $28^{\circ}$  half angle) attached to each LED to collect the light. A fan (YCCFAN D02X-05TS1 02 5V DC) was installed in the display part to dissipate the heat of the LEDs. The diameter of the pipes for dry air is 8 mm, while the diameter of the pipes for mist transport is 15 mm, because the water droplet is resistant to mist transport.

#### 4. Basic Performance Evaluation

To evaluate the basic performance of the developed humid sensation device, the intensity of light heating by LEDs and the ability to control the set target humidity were verified.

##### 4.1. Evaluating the Control of LED Light Heating

The temperature rise caused by LED light heating of a silicon sheet coated with blackbody spray (Ichinen TASC0, TA410KS) was measured by a non-contact temperature sensor (OMRON, D6T-44L-06H). The brightness of the LEDs can be controlled by Pulse Width Modulation (PWM). In the experiment, the duty cycle of the LEDs was set in five steps (20, 40, 60, 80, and 100 %). Ten measurements were taken under each condition.

**Table 1:** Relationship between the duty cycle and the mean and standard deviation of the rate of temperature change

Duty Cycle(%)	Rate of temperature change( $^{\circ}\text{C}/\text{s}$ )
20	$0.15 \pm 0.021$
40	$0.35 \pm 0.021$
60	$0.56 \pm 0.027$
80	$0.76 \pm 0.015$
100	$0.94 \pm 0.072$

The relationship between the LED duty cycle and the temperature change rate of the silicon sheet is shown in Table 1. The coefficient of determination,  $R^2$ , was 0.98. The duty cycle of the LED light heating was set to 35% empirically, and used in all experiments of this study. This duty cycle achieves a temperature change rate of  $0.3^{\circ}\text{C}/\text{s}$  with the silicon sheet.

##### 4.2. Measurement of the Effect of LED Light Heating on the Temperature and Humidity Change Near the Sponge

Light heating was applied to a sponge with a water content of about 30 % to simulate skin, and the humidity and temperature in the vicinity of the sponge were measured. The humidity and temperature are measured at three different heights (3, 11, and 19 mm) from the sponge, as shown in Fig. 5. The device was held in place for 60 s to stabilize the temperature and humidity sensor. Then, the sponge was light heated for 30 s, and the humidity and temperature were measured during that time. Ten measurements were taken. The duty cycle for the LED light heating in this experiment was set to 35%, as described above.

Fig. 6 shows the humidity and temperature changes from the initial condition at each distance from the sponge. A one-way ANOVA was performed for the humidity and temperature changes, respectively, with the distance from the sponge as a factor. Statistical values for the left and right-side analysis of Figure 6 were  $F(2,27)=107.73$  and  $F(2,27)=20.29$ , respectively. Since significant differences were obtained, multiple comparisons were made using the Tukey method. The humidity increase of about 12 %RH, which is relative humidity, was observed at a height of 3 mm, and significantly different from the humidity increase at other heights ( $p < 0.05$ ). There was also a significant temperature change at 3 mm height compared to 11 and 19 mm heights, although the measured temperature change was slight. Light heating caused the changes both in humidity and temperature in the vicinity of the sponge.

##### 4.3. Evaluating Humidity Control Systems

The target humidity was set at five levels (10, 30, 50, 70, and 90 %RH), and the values of the humidity sensors (Sensirion, SHT85) in the two mix parts are measured five times each to evaluate the steady-state characteristics of humidity control. Steady state is considered to be achieved when the deviation remains within 10 %RH of each target humidity for more than 20 s. The average of the measured values during that period is the steady-state value, and the difference between the steady-state and target values is the steady-state deviation.

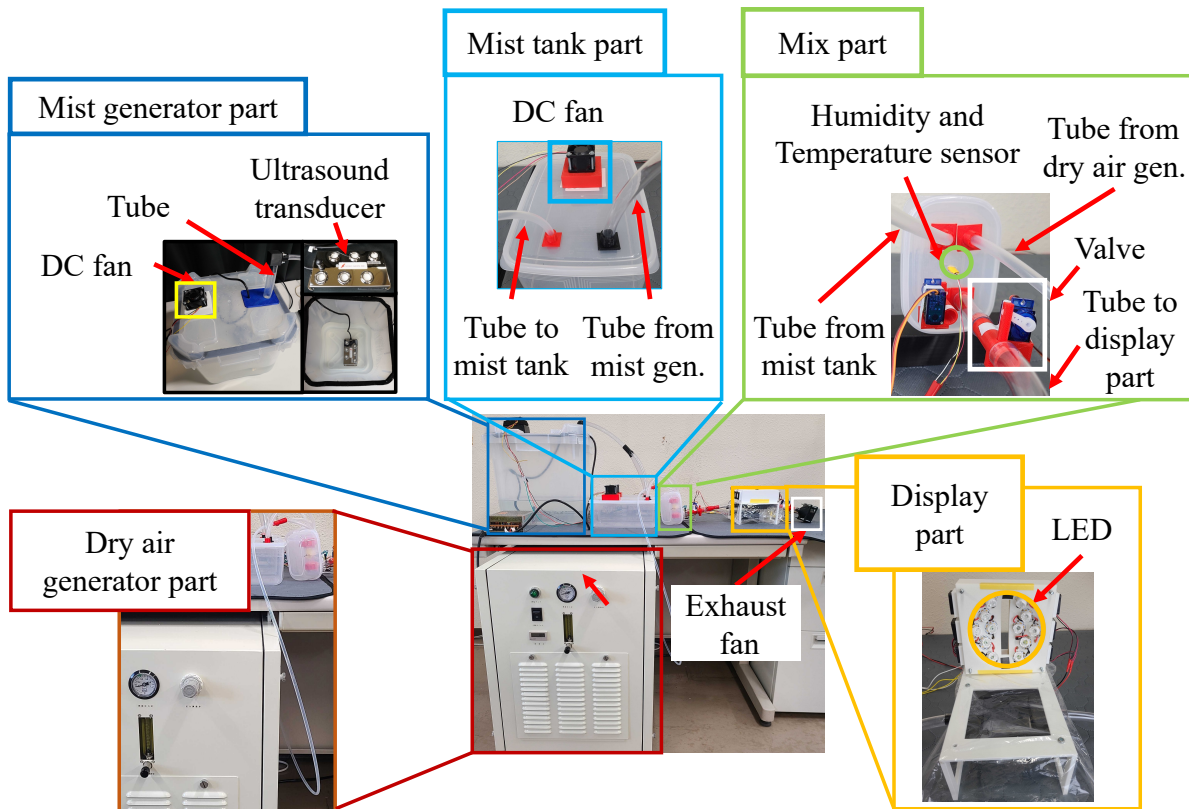


Figure 3: Prototype system

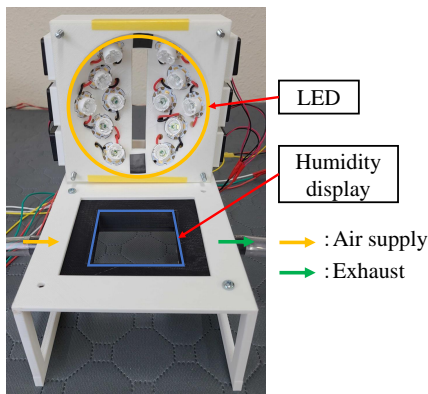


Figure 4: Exploded view of the display part to show its configuration

Fig. 7 shows the humidity change for each target value for the humidity control results in the mix part 1, as an example of the mix parts. The dotted line plots the actual measured value at each measurement session, and the solid line plots the average of five measurements at each target value. The results showed that it took about 30 s at longest to reach the target value. However, as we describe

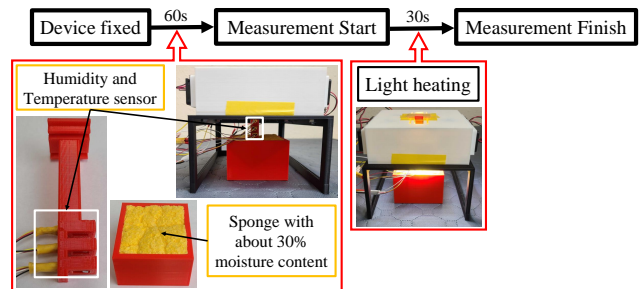
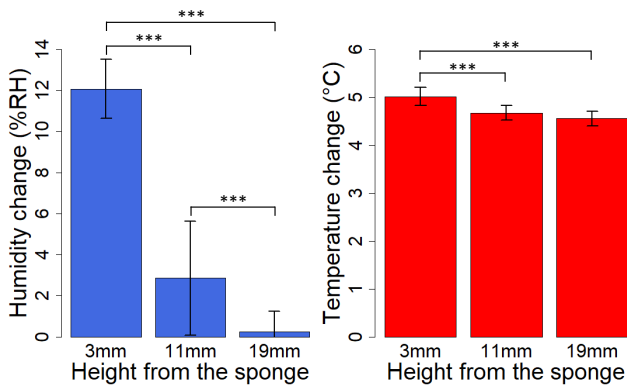


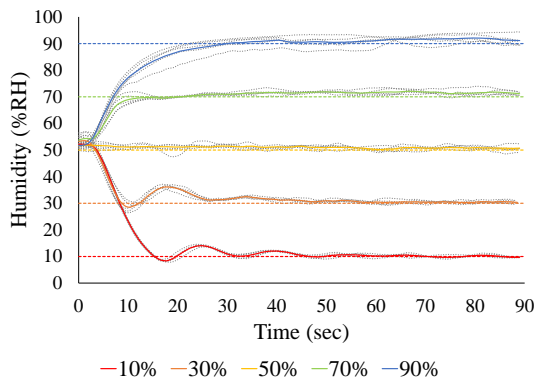
Figure 5: Experimental procedure to verify whether light heating of a sponge with about 30 % moisture content increases the humidity in the vicinity of the sponge.

below, each trial in the human study takes more than 30 s including evaluation time by participants. Thus, the system has enough time to prepare the humid air for the next trial.

Table 2 shows the results of humidity control in the mix part as a steady-state characteristics. It was shown that two humidity controls were possible at the same time in a stable manner, while the errors have a slight difference within 1.0 %RH between the two mix parts. Steady-state deviations in humidity control were less than 5 %RH, indicating that stable humidity control was possible.



**Figure 6:** The results of humidity and temperature changes due to LED light heating measured at 3, 11, and 19 mm heights from the sponge with about 30 % moisture content.



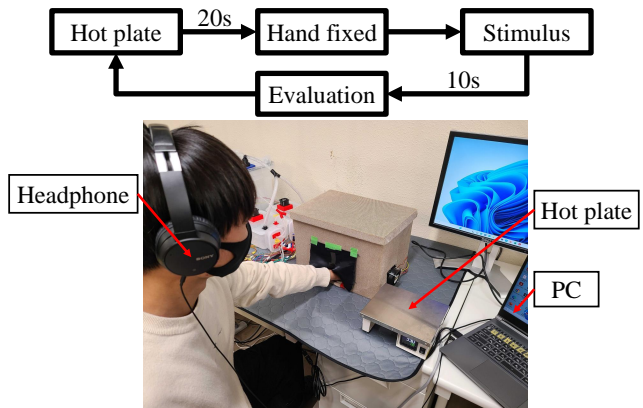
**Figure 7:** Result of the humidity control in the mix part1 as an example

## 5. Evaluation of Humid Sensation

To investigate whether this device can be used to present humid sensations of different intensity, such as low and high humidity, we tested how the user perceives the humidity of the presented stimuli by presenting stimuli that combine LED on/off and steady/temporal humidity on the back of the left hand. The participants were asked how they felt about the humidity of the presented stimuli. The experiment was conducted on eight participants between the ages of 22 and 27 ( $23.75 \pm 1.49$ ), one female and seven males. The participants were not involved in the development of the system. Each participant received approximately USD 8 in the form of an Amazon gift card as monetary compensation. The recruitment of participants and experimental procedures were approved by the Ethical Committee of the Institute of Systems and Information Engineering, University of Tsukuba, Japan (approval number 2021R534). All participants provided written informed consent before participating in the study.

**Table 2:** Evaluation of steady-state characteristics in mix part1

target level (%RH)	error in mix part 1 (%RH)	error in mix part 2 (%RH)
10	1.5	1.2
30	2.7	3.6
50	1.4	0.71
70	0.39	0.082
90	1.1	0.63



**Figure 8:** Experimental procedures for evaluating the wetness sensation in steady-state stimuli

### 5.1. Experiment 1: Experiments to Evaluate Humid Sensation in Response to Constant Stimulation

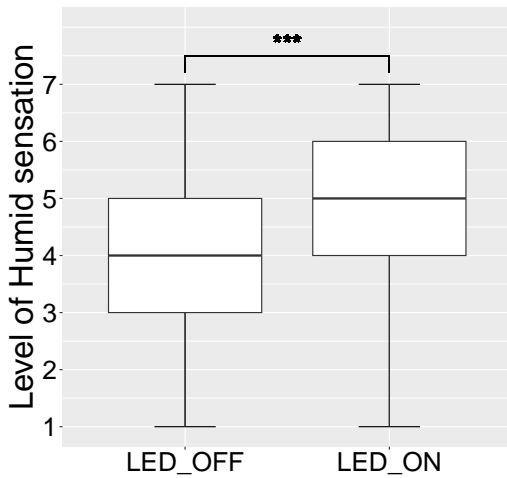
In Experiment 1, induced humid sensations are studied under the combined conditions of LED light heating and the transported humid air.

#### 5.1.1. Experimental Conditions

As shown in Fig. 8, participants were instructed to place the back of their left hand on a hot plate set at 33 °C for 20 s before the stimuli were presented, and then fix their hand in the device so that the display part of the device would present the stimuli to the back of their left hand. Stimuli were a combination of five levels of humidity (10, 30, 50, 70, and 90%RH) and two conditions of LED light (ON and OFF). We presented each designed stimuli at random for three trials, resulting in 10 stimuli  $\times$  3 trials = 30 trials. After the 10 s stimulus presentation, the participants were asked to rate the humidity on a 7-point Likert scale (7: very high humidity, 6: high humidity, 5: rather high humidity, 4: indifferent, 3: rather low humidity, 2: low humidity, 1: very low humidity). The display part was placed in a box to shade the LED light during the stimulus presentation. To avoid the influence of fan and environmental noise, participants wore noise-canceling headphones and listened to white noise while performing the task. The duration and strength of heating was designed from the limitation for safety. Ten seconds and the duty cycle 100 % in the current configuration gets closer to the temperature to induce pain around 45 °C. Therefore, the duration

**Table 3:** Mean and standard deviation of humid sensation to steady-state stimuli

Humidity (%RH)	LED	Humid sensation
10	OFF	3.5±1.4
30	OFF	3.5±1.2
50	OFF	3.3±1.2
70	OFF	3.7±1.5
90	OFF	4.4±1.5
10	ON	4.8±1.4
30	ON	4.8±1.4
50	ON	5.1±0.86
70	ON	4.7±1.1
90	ON	4.8±1.4

**Figure 9:** Effects of LED light on humid sensation

for the LED light heating was set to ten seconds in this experiment, while the duty cycle was set to 35%, as described above. The room temperature was not controlled, but about 20 to 30 degrees Celsius. The skin temperature was controlled using a hot plate before each stimulation trial. No measurement was conducted after the stimulation trial, but basic measurement using a silicon sheet was performed. Eight participants joined in both experiments. To avoid fatigue, participants took a 30-second break every five trials in the experimental protocol.

### 5.1.2. Results and Discussions

Table 3 shows the results of the evaluation of humid sensation when the combination of LED light ON/OFF and humidity (10, 30, 50, 70, 90%) was presented for 10 seconds in a steady-state stimulus.

A Friedman test was conducted to determine whether the factors of LED light heating and humidity supplied to the presentation area had an effect on the humid sensation at a significance level of 5%. The results showed that there was a significant difference in LED light heating, while there was no significant difference in humidity. As to LED light heating, the results of pairwise comparisons using Wilcoxon signed rank test showed a significant difference between

ON and OFF on the humid sensation, as shown in Fig. 9. As to humidity, the results showed that it is difficult to induce different humid sensations from the air simply by presenting mist with different humidity levels. As a result, light heating by LED was effective in inducing the humid sensation.

## 5.2. Experiment 2: Experimental Evaluation of Humid Sensation in Response to Time-Division Stimuli

In Experiment 2, in order to investigate the possibility of presenting different intensity of humid sensations by temporal change of stimuli, we evaluate the humid sensation when the stimulus pattern is switched from the first stimulus to the second stimulus in time.

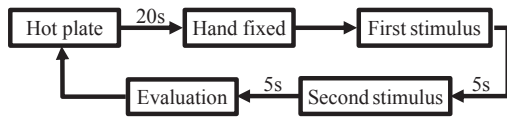
### 5.2.1. Experimental Conditions

As shown in Fig. 10, participants adjusted the temperature of the back of their left hand using a hot plate set at 33 °C for 20 s and fixated their hand in the device before the stimuli, as in Experiment 1. After the first stimulus for 5 seconds, the second stimulus for 5 seconds was presented to the experimental participants, who rated the sensation of the second half of the stimulus on a 7-point Likert scale (7: very high humidity, 6: high humidity, 5: rather high humidity, 4: indifferent, 3: rather low humidity, 2: low humidity, 1: very low humidity). Four stimulus patterns were prepared by combining two conditions of air humidity (90 %RH and 10 %RH) and two conditions of LED (ON and OFF). A total of 16 combinations of the first 4 patterns and the second 4 patterns were randomly presented 3 times each for a total of 48 trials. As in Experiment 1, the display part was placed inside a box and white noise was played through noise-canceling headphones. The duration for the LED light heating was set to ten seconds in total as well as Experiment 1. The duty cycle for the LED light heating in this experiment was set to 35%, as described above.

### 5.2.2. Results and Discussions

Table 4 shows the results of the evaluation of the humid sensation when the stimuli were presented in a time-division stimulus patterns.

A Friedman test was conducted to determine whether the factors of LED light heating in the first and second halves and supplied humidity in the first and second halves had an effect on the humid sensation at a significance level of 5%. The results showed there was no significant difference in humidity both in the first and second halves, while there was significant differences in LED light heating both in the first and second halves. Therefore, we grouped the stimuli into groups by the combination of ON/OFF of the LED light in the first stimulus and ON/OFF of the LED light in the second stimulus. Fig. 11 shows the results of humid sensation evaluation for the combination of ON/OFF of the LED for the first and second halves stimuli. Statistical values for the analysis were chi-squared = 71.95, df = 3, p-value = 1.631e-15 < 0.05. Multiple comparisons were made using the Wilcoxon signed rank test with Bonferroni correction. When the first stimulus is A and the second stimulus is B, it is denoted as stimulus change pattern (A->B). There was a significant difference in humid sensation between the stimulus change pattern (OFF->OFF) and (OFF->ON). There was also a significant



**Figure 10:** Experimental procedures for evaluating the humid sensation in time-division stimuli

difference in humid sensation between the stimulus change pattern (ON->OFF) and (ON->ON).

The median value of humid sensation in the stimulus change pattern (OFF->OFF) was 4 (indifferent), indicating that humid sensation was not generated. On the other hand, in the case of the stimulus change pattern (ON->ON) and (OFF->ON), the median value of the humid sensation was 5 (rather high humidity), indicating the effect of making the participants feel high humidity. In the case of the stimulus change pattern (ON->OFF), the median value of humid sensation was 3 (rather low humidity), indicating the effect of making the participants feel low humidity.

As to the effects of temporal change, no significance difference was found between the stimulus change pattern (OFF->OFF) and (ON->OFF) as well as between the pattern (ON->ON) and (OFF->ON). However, the results suggested the temporal change reduced variability of the induced humid sensations, because the standard deviations in the changing conditions (ON->OFF) and (OFF->ON) were smaller than those in the unchanged conditions (OFF->OFF) and (ON->ON). It would be useful for the humid sensations display.

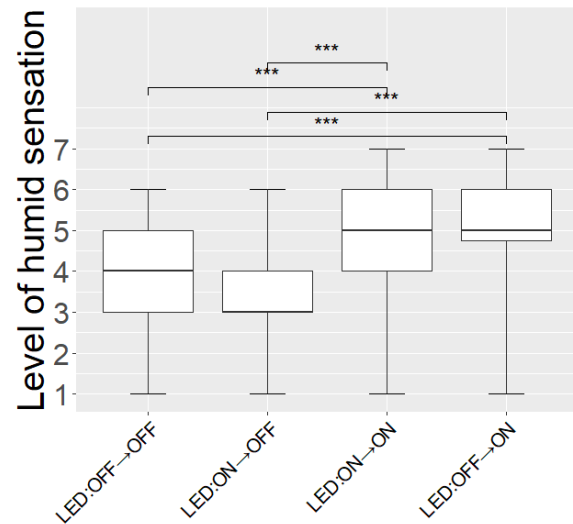
We have realized a novel humid sensation display. However, there are a couple of limitations. First, we have measured the increase of humidity and temperature using the sponge with the water content of about 30 %. This is because the water content of a sponge can be strictly controlled and its porous structure is large, so the humidity and temperature in the large space over the surface will change and can be easily measured with the current humidity sensor of 0.1 %RH precision and 8 s time constant. However, it is important to investigate the effect of heating the human skin on the humidity change. Unlike the sponge, the human skin has minute porous structures that store moisture inside the body, so a quick and more sensitive sensor is needed to measure the state. Second, we have only tested with the participants from the similar area in the world that would have similar cultural background, and people with different cultures would have different feeling even with the same stimuli. Thus, we will test with the participants from a variety of countries in the world in future.

### 5.2.3. Limitations and Challenges

If the skin area in contact with humid air is large, we feel humidity. However, if the skin area in contact with humid air is small, it is difficult to feel humidity. Our hypothesis is that LED light enhances the humidity close to skin and enables it to induce humidity even if the skin area in contact with humid air is small. According to the results of Experiment 1 and 2, the light heating by LED

**Table 4:** Mean and standard deviation of humid sensation to steady-state stimuli

First stimulus		Second stimulus		
Humidity (%RH)	LED	Humidity (%RH)	LED	
10	OFF	10	OFF	3.4±1.2
10	OFF	90	OFF	3.8±1.4
90	OFF	10	OFF	3.8±1.3
90	OFF	90	OFF	3.9±1.3
10	ON	10	OFF	3.3±1.0
10	ON	90	OFF	3.3±1.2
90	ON	10	OFF	3.5±1.1
90	ON	90	OFF	3.6±1.1
10	OFF	10	ON	5.1±0.86
10	OFF	90	ON	4.9±1.1
90	OFF	10	ON	4.6±1.5
90	OFF	90	ON	4.7±1.4
10	ON	10	ON	4.7±1.3
10	ON	90	ON	4.5±1.5
90	ON	10	ON	4.8±1.5
90	ON	90	ON	5.0±1.0



**Figure 11:** Results focused on the humid sensation caused by LED light heating

was effective in inducing the humid sensation. However, based on the measurement test, there is a possibility that humidity increase close to the skin as well as temperature increase by light heating possibly helped participants feel humid sensations. As to the experimental conditions, the experimenter asked the participants to answer the intensity of humid sensations, not thermal sensations, based on the Likert scale. However, further investigation with the two questions, one for humid sensations and the other for thermal sensations, will reduce the chance to get the responses from the participants based on the thermal sensation. Regarding the Likert scale options, although we prepared "low humidity" as the opposite of "high humidity," in the future we could use the word "high dryness" as the opposite not to omit possible responses of dryness. As we described in the experimental conditions, we adjusted skin temperature of participants to 33 °C using a hot plate before ap-

plying stimulus. However, we did not adjust moisture on the skin. That would be a limitation of this study. From the viewpoint of simulating sensations, we focused on simulating humid sensation and have never tested dry sensations using the current system. In addition, the current configuration of the humidity representation method depends on thermal stimuli. Therefore, to propose a method to induce thermal and humidity sensations independently is a future work. The weakness of this paper is the evaluation of human subjects with small number of participants. It would be desirable to conduct more in-depth studies by increasing the number of experimental participants and conducting interviews and questionnaires.

## 6. Conclusions

In this study, we focused on changing the humidity in the vicinity of the skin and proposed a method of making it highly humid by heating the skin with light. Based on this method, we developed a device that is able to present the humid sensations of different intensities. In the experiment, stimuli were presented in a steady state by combining the on/off of LED light and the humidity (10, 30, 50, 70, and 90 %RH) supplied to the presenting area. The results of the experiment showed that heating by LED light had the effect of inducing humid sensations. On the other hand, the results found no statistical difference in humid sensations by supplying air of different humidity, reconfirming the conventional issue. In an experiment in which stimuli were presented in a time-division pattern combining 10 and 90% humidity and LED light ON and OFF, it was suggested that the variation in the humid sensation generated by switching the stimuli in time-division became smaller. Note that in this paper we were unable to exclude the effect of temperature changes on humidity sensation. This is one of the issues to be addressed in the future. Furthermore, it is expected that the proposed humid sensation display will be used to realize a VR experience that represents a humid ambient environment by stimulating the local skin efficiently.

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