Influence of temperature and humidity of ambient air on sensation of dryness during respiration

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Abstract

To create an optimal indoor thermal environment, it is necessary to identify the environmental conditions that cause a sensation of dryness. Dryness is experienced in various parts of the human body such as the nose, mouth, throat, eyes, and skin: this study focuses on dryness in the airway. The relationship between the sensation of dryness and environmental factors such as the ambient air temperature and humidity (vapor pressure) was analyzed based on experiments performed on four subjects. This study analyzed the sensation of dryness experienced in six parts along the respiratory tract and the temperature of air inhaled/exhaled at the airway aperture of each of the four subjects under different conditions of humidity and temperature maintained in an artificial climate chamber. The route of respiration was restricted to the nose or the mouth by blocking the other aperture. The experimental results revealed that the temperature of exhaled air was lower and the sensations of dryness in the nose, mouth, and throat were more intense in the case of low humidity under a constant temperature. These results suggest that an increase in the evaporation rate in the airway may cause a sensation of dryness. Further, the experimental results revealed that in the case of high temperature and constant vapor pressure, the sensation of dryness tended to be more intense. This suggests that higher ambient temperature increases the evaporation rate in the airway owing to the increase in the saturated vapor pressure in the inner surface of the airway.

Keywords: Sensation of dryness, Airway, Temperature, Humidity, Subject experiment

1. Introduction

Under low-humidity conditions, individuals sometimes experience dryness in the airway. A survey has indicated that among different parts of the body, the throat most often experiences discomfort due to dryness (Takada et al. 2013). Appropriate control of the hygrothermal environment is necessary to avoid this discomfort. However, the existing quantitative information is limited. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers has determined the “acceptable range” as thermally neutral conditions based on the predicted mean vote (PMV), and it does not indicate the specific limit of low humidity, although discomfort caused by dryness due to low humidity is noted in the document (ASHRAE 2017). In other words, the threshold of humidity beyond which discomfort due to low humidity is experienced is yet to be determined (Derby et al. 2017, Kakitsuba 2018): thus it must be experimentally investigated along with the influence of ambient air temperature.

A few attempts have been made to analyze the response of humans to low humidity. For whole-body responses, several experimental observations have been made. Winslow et al. (1937) conducted experiments for many combinations of temperature and humidity and quantitatively determined the loss of heat and moisture from the human body. Andersen et al. (1974) exposed subjects to a low-humidity environment at 23 °C and 9% relative humidity (rh) for 78 h and surveyed the responses to humidity. Fang et al. (2004) conducted experiments on subjects under several temperature and humidity conditions while considering the indoor air quality.

In a study that focused on airways and respiration, Karaki et al. (2004, 2005) reported the influence of low humidity on the nasal mucous membrane; saccharin
clearance times were measured by exposing subjects to humidity conditions of 10%, 30%, and 50% relative humidity at 25 °C. They identified significant differences in the case of 10% rh. The relationship between the hygrothermal state of inhaled air and mucosal function of the airway has been investigated based on data using respiratory tract physiology and humidification (Williams et al. 1996).

In basic studies on the airway conducted from the perspectives of indoor air humidity control and physiology, Seeley (1940) and Keck et al. (2000) measured the temperature and humidity in the nasal cavity. The temperatures of exhaled air from the nose and mouth were measured under different temperature and humidity conditions (McCutchan et al. 1951, Cole 1953, Höppe 1981). Recently, air flow in the airway or nose has been analyzed using computational fluid dynamics (CFD) (Keck et al. 2010, Li et al. 2012, Ge et al. 2013, Villafruela et al. 2013, Phuong et al. 2015). CFD has also been used to analyze the distribution of air around the human body during respiration to evaluate the humidity, temperature, or quality of inhaled air (Gao et al. 2004, Zhu et al. 2005, Gao et al. 2006, Zhang et al. 2011). The air flow dynamics during coughing, breathing, and talking were studied experimentally to create a model that can predict the transmission of airborne diseases (Gupta et al. 2009, Gupta et al. 2010). Additionally, discomfort associated with the respiration of warm air, humidity, temperature, or quality of inhaled air (Gao et al. 2004, Zhu et al. 2005, Gao et al. 2006, Zhang et al. 2011). The air flow dynamics during coughing, breathing, and talking were studied experimentally to create a model that can predict the transmission of airborne diseases (Gupta et al. 2009, Gupta et al. 2010). Additionally, discomfort associated with the respiration of warm air under humid conditions was discussed (Toftum et al. 1998).

This brief review of previous studies indicates that there are several approaches that can be implemented to determine airway responses during respiration under different indoor temperature and humidity conditions. However, the research that has been conducted on the sensation of dryness in the airway is limited. First, the relation between the sensation of dryness and the indoor air temperature and humidity conditions must be clarified to apply this information to the design and control of indoor thermal environments. Second, the relationship between the moisture content in the mucous membrane (or rate of evaporation) and the sensation of dryness must be elucidated to develop a model that can predict the sensation of dryness. Humidity and temperature can be related to the sensation of dryness because the saturated vapor pressure, which is a function of the temperature of the body surface, accounts for the evaporation rate and the moisture in the mucous membrane.

In this study, the influences of humidity and temperature of ambient air on the sensation of dryness and on the hygrothermal state of the airway during respiration were investigated by exposing subjects to different levels of ambient-air humidity (vapor pressure) and temperature. The temperature of exhaled air measured at the apertures of the nose and mouth were observed as an indicator of the hygrothermal state of the airway.

2. Method of subject experiments

The experiments were conducted in winter season in Japan (December–January). Four healthy male subjects (aged 21–23 years) participated in the experiments (Table 1). Two series of experiments were conducted: Experiment 1 investigated the change in vapor pressure under constant temperature, whereas Experiment 2 investigated the change in air temperature with constant vapor pressure, as shown in Figure 1. Experiments 1 and 2 were conducted on different days. During each experiment, the subjects remained in an artificial climate chamber in which the air temperature and humidity was controlled automatically via a set program with mechanically ventilated system. In Experiment 1, the air temperature was kept at 29 °C, and the vapor pressure was set at three levels: 320, 1650, 3300 Pa (8, 40, 85% in relative humidity, respectively). In Experiment 2, the vapor pressure was kept at 650 Pa, and the air temperature was set at two levels; 18 and 29 °C (30, 15 % rh, respectively). In typical situations, humans inhale/exhale air through the two routes of respiration – the nose and the mouth. In this experiment, the route was limited to the nose or mouth by blocking one of the routes with surgical tape. The experiments

| Gender | Age [year] | Height [cm] | Weight [kg] |
|--------|-----------|-------------|-------------|
| A      | Male      | 21          | 172         | 63          |
| B      | Male      | 22          | 182         | 62          |
| C      | Male      | 21          | 170         | 60          |
| D      | Male      | 23          | 169         | 58          |

Table 1 Details of the four subjects who participated in the experiments.

| Instrument | Air temperature at apertures of nose/mouth | Thermocouple (0.2mm in diameter), Data logger (Keyence NR-1000) |
|------------|--------------------------------------------|-----------------------------------------------------------------|
|            | Air temperature and humidity of ambient air | Temperature and humidity sensor with data logger (Especmic RS-12) |
|            | Skin temperature at neck                    | Temperature sensor with data logger (Gram LT-8)                  |

Table 2 Measured items.
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Involving respiration through the nose and mouth were conducted sequentially. As shown in Figure 1, after entering the climatic chamber, the subject rested in a sedentary position for 20 min under the conditions of 29 °C, 320 Pa (8% rh) (Experiment 1) or 18 °C, 650 Pa (30% rh) (Experiment 2). Subsequently, the first measurement was taken. The subjects were not aware of the conditions of air temperature and humidity. They wore their own clothing (approximately 0.6–0.8clo) and were in a sedentary position throughout the experiments. The air velocity in the climatic chamber was kept 0.2–0.3 m/s for the duration of the experiments. The mean radiant temperature was approximately equal to the air temperature: The entire surface of the ceiling and floor was made of a punched stainless metal panel, and the air controlled to the set point temperature and humidity was supplied from the surface of ceiling and exhausted to the entire surface of floor; for walls, the curtains covered the entire surfaces that did not touch the wall. Drinking water during the experiment was not permitted.

The investigation of each environmental condition continued for 60 min. The subjects was rested in a sedentary position without blocking their respiration for 20 min between each environmental condition (approximately 5 min was taken to change the vapor pressure and temperature levels). A total of 10 min were taken to replace the tube to measure the air temperature at the aperture when switching between the nose and the mouth conditions. The rating of the sensation of dryness was performed during “measurement” period (Figure 1) within a 5 min interval.

Dryness was rated using the scale shown in Figure 2. The subject was requested to rate the sensations of six parts along the respiratory tract for rating the sensation of dryness.

![Figure 1](originally in Japanese)

![Figure 2](scale for rating the sensation of dryness and the schematics of the parts along the respiratory tract for rating the sensation of dryness.)
In this study, for the psychological responses of the subjects, Student’s t-test was used to compare the differences caused by exposed humidity or temperature. The P values (<0.05) were considered to be statistically significant. All statistical analyses were conducted using Microsoft Excel 2013.

The experiments were conducted after obtaining informed consent from the subjects as dictated by Helsinki Declaration.

3. Results of subject experiments

3.1. Experiment 1 (change in air humidity)

In Experiment 1, the air temperature was kept constant and air humidity (vapor pressure) was changed. The air temperature and vapor pressure around the subjects are shown in Figure 4. The air temperatures measured at the aperture of the nose and mouth at each level of vapor pressure are shown in Figure 5. The last minute of “measurement” depicted in Figure 1, was selected as the time-point of analysis. The temperature showed cyclic fluctuation with inhalation and exhalation. The temperature of the expired air was higher because it is significantly affected by the inner environment in the airway, whereas the temperature of the inspired air is close to that of the ambient air. Based on this, it is possible to determine the respiration phase by using the temperature data. For one temperature cycle, the time from the start of the temperature rise to the start of the decrease was associated with exhalation, and the remainder was associated with inhalation. Therefore, the temperature data during exhalation reflects the temperature in the airway. The maximum temperature of a cycle became lowered with decrease in the humidity condition (Figure 5) that is caused by the difference in evaporation rate in the airway. In contrast, the minimum temperature was approximately the same for the three humidity levels. This temperature change was consistent whether respiration occurred through the mouth or the nose.

Figure 6 shows the air temperature at the nose and mouth aperture averaged across the four subjects for the observed 1 minute, whereas only representative data from Subject A is shown in Figure 5. The temperature at the aperture decreased as the ambient vapor pressure decreased. This occurred in all the four subjects, regardless of respiration paths (nose and mouth) (Table 3). The difference in average air temperature at the aperture reached 1.7 K between the lowest and highest humidity.

The skin temperature measured at the side of the
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Figure 5. Air temperature at the aperture (Subject A, 29 °C, (a) 320Pa, (b) 1650Pa, (c) 3300Pa).

Figure 6. Temperature measured at the aperture of the nose or mouth during Experiment 1. Ratings are over an average of 1 min. Standard deviations are shown using bars.
neck is listed in Table 3. With changing humidity, the skin temperature was minimally changed. This suggests that evaporation rate in the airway caused the change in air temperature at the aperture of nose or mouth during respiration, along with the change in vapor pressure.

The respiration rate was estimated based on the temperature data (Table 3). No significant changes in the respiration rate due to humidity were identified for the nose respiration cases.

Figure 7 shows the sensation of dryness at six points in the respiratory tracts in Figure 2. For the case of respiration through the nose (Figure 7 (a)), the sensation of dryness intensified with decrease in the humidity level. This tendency occurred in all the subjects (Table 3), and was particularly noticeable at the nose aperture, the nasal cavity, and the pharynx. The mouth aperture was closed during the case of respiration through the nose, resulting in the evaporation at the inner surface of the airway and was enhanced primarily in the nose and in the throat. When respiration occurred through the mouth (Figure 7 (b)), the sensation of dryness at the lips, oral cavity, pharynx, and larynx was clearly different between the three humidity conditions.

3.2. Experiment 2 (change in air temperature)

In Experiment 2, the humidity (vapor pressure) was kept constant and the air temperature was changed. The air temperature and vapor pressure around subjects are shown in Figure 8. The air temperatures measured at the aperture of the nose and mouth at each level of air

Figure 7. Sensation of dryness at several points of the airway, (a) results obtained during respiration through nose, (b) results obtained during respiration through mouth during Experiment 1. Ratings are over an average of 1 min. Standard deviations are shown using bars.
temperature are illustrated in Figure 9. The temperature at the aperture of the nose and mouth increased in the higher air temperature condition. There was no effect of temperature on the respiration rate (Table 4). As shown in Figure 10, the sensation of dryness along the respiratory tracts intensified in the higher air temperature condition for most parts along the airways, regardless of the airway path, although the differences were not statistically significant for most parts.

4. Discussion

4.1. Sensation of dryness and moisture evaporation in airway

From Experiment 1, it was observed that the temperature of the exhaled air was lower for a lower vapor pressure of the inhaled air, even though the temperature of the inhaled air was constant. This might mean that the surface temperature in the airways decreased significantly due to the decrease in ambient vapor pressure at constant air temperature. The enhanced evaporation rate in the airway in the case of lower ambient vapor pressure could be the reason for this. On the other hand, the sensation of dryness also became more intense with lower vapor pressure of the inhaled air. These findings suggest that the evaporation rate in the airway is related to the sensation of dryness. For the condition of low humidity, the evaporation in the airway might be enhanced to cause a more intense sensation of dryness. From Experiment 2, it was observed that the air temperature at the aperture of the airway increased significantly for an increased temperature and constant vapor pressure. At the same time, the sensation of dryness became more intense, even though it was not

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Table 3 Measured results for each subject during Experiment 1.

| Air temperature at nose aperture [°C] | Respiration | Subject | 120Pa | 1650Pa | 3300Pa |
|--------------------------------------|-------------|---------|-------|--------|--------|
| through nose                          |             |         |       |        |        |
| Subject A                            | 31.0        | 32.2    | 32.6  |
| Subject B                            | 31.4        | 32.6    | 33.7  |
| Subject C                            | 32.1        | 32.3    | 33.6  |
| Subject D                            | 31.3        | 32.1    | 32.9  |
| average                              | 31.5        | 32.3    | 33.2  |
| through mouth                         |             |         |       |        |        |
| Subject A                            | 32.8        | 32.9    | 34.5  |
| Subject B                            | 32.6        | 32.8    | 33.0  |
| Subject C                            | 32.1        | 32.3    | 33.6  |
| Subject D                            | 31.9        | 32.3    | 33.3  |
| average                              | 32.4        | 32.6    | 33.5  |
| Skin temperature at neck [°C]        |             |         |       |        |        |
| through nose                          |             |         |       |        |        |
| Subject A                            | 34.9        | 34.9    | 35.2  |
| Subject B                            | 34.9        | 34.9    | 35.2  |
| Subject C                            | 34.9        | 34.9    | 35.2  |
| Subject D                            | 35.3        | 35.2    | 35.4  |
| average                              | 34.9        | 35.0    | 35.2  |
| through mouth                         |             |         |       |        |        |
| Subject A                            | 14.4        | 14.8    | 15.2  |
| Subject B                            | 14.0        | 16.0    | 14.4  |
| Subject C                            | 18.4        | 18.4    | 17.6  |
| Subject D                            | 18.4        | 18.0    | 17.2  |
| average                              | 16.3        | 16.3    | 16.1  |
| Respiration rate [times/min]         |             |         |       |        |        |
| through nose                          |             |         |       |        |        |
| Subject A                            | 13.2        | 18.0    | 13.2  |
| Subject B                            | 16.0        | 16.4    | 16.8  |
| Subject C                            | 16.8        | 17.6    | 21.6  |
| Subject D                            | 18.4        | 20.4    | 24.0  |
| average                              | 16.1        | 18.1    | 18.9  |
| through mouth                         |             |         |       |        |        |
| Subject A                            | 2           | 2       | 0     |
| Subject B                            | 2           | 0       | -1    |
| Subject C                            | 2           | 0       | -1    |
| Subject D                            | 2           | 0       | 0     |
| average                              | 2.0         | 0.3     | -0.5  |
| Vote of sensation of dryness at nose aperture | | | |
| through nose                          |             |         |       |        |        |
| Subject A                            | 3           | 1       | -2    |
| Subject B                            | 3           | 1       | -1    |
| Subject C                            | 3           | 1       | -2    |
| Subject D                            | 3           | 2       | 1     |
| average                              | 3.0         | 1.3     | -1.0  |

Table 4 Measured results for each subject during Experiment 2.

| Air temperature at mouth aperture [°C] | Respiration | Subject | 18°C | 29°C |
|----------------------------------------|-------------|---------|------|------|
| through nose                           |             |         |      |      |
| Subject A                              | 24.2        | 30.0    |
| Subject B                              | 26.3        | 30.9    |
| Subject C                              | 26.5        | 30.5    |
| Subject D                              | 25.8        | 30.6    |
| average                                | 25.7        | 30.5    |
| through mouth                          |             |         |      |      |
| Subject A                              | 27.2        | 31.7    |
| Subject B                              | 28.7        | 31.3    |
| Subject C                              | 25.5        | 31.4    |
| Subject D                              | 26.6        | 31.5    |
| average                                | 27.0        | 31.5    |
| Skin temperature at neck [°C]          |             |         |      |      |
| through nose                           |             |         |      |      |
| Subject A                              | 31.6        | 34.6    |
| Subject B                              | 33.1        | 34.8    |
| Subject C                              | 32.5        | 34.8    |
| Subject D                              | 32.4        | 34.5    |
| average                                | 32.4        | 34.6    |
| through mouth                          |             |         |      |      |
| Subject A                              | 15.2        | 14.0    |
| Subject B                              | 12.8        | 14.0    |
| Subject C                              | 17.6        | 18.0    |
| Subject D                              | 18.0        | 18.0    |
| average                                | 15.9        | 16.0    |
| Respiration rate [times/min]           |             |         |      |      |
| through nose                           |             |         |      |      |
| Subject A                              | 16.4        | 15.6    |
| Subject B                              | 18.0        | 13.2    |
| Subject C                              | 18.0        | 18.8    |
| Subject D                              | 18.8        | 18.8    |
| average                                | 17.8        | 16.6    |
| through mouth                          |             |         |      |      |
| Subject A                              | 1           | 1       |
| Subject B                              | 1           | 1       |
| Subject C                              | 1           | 1       |
| Subject D                              | 1           | 1       |
| average                                | 1.0         | 1.0     |

The values of temperatures and respiration rates in this table are the averages for 1 min at the end of each “measurement” shown in Figure 1, and the rating of sensation of dryness was recorded at the end of each “measurement”.

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statistically significant. This suggests that the evaporation rate in the airway increases due to the temperature increase, because the increase in saturated vapor pressure at the surface of the airway enhances evaporation.

The current experiment demonstrates that the intensity of the sensation of dryness was stronger in the cases of lower vapor pressure and higher temperature. These results are in agreement with the mechanism of evaporation in moist materials. The lower vapor pressure of ambient air increased the vapor pressure difference, thereby enhancing the evaporation rate. The higher temperature increased the moist surface temperature by causing the saturated vapor pressure of the surface to increase, thereby enhancing the evaporation. These results offer a base for modeling hygrothermal behavior in the airway.

4.2. Experimental conditions and methods

4.2.1. Influence of blocking either nose or mouth and cylinder attachment

In a natural state, human respiration occurs through both the nose and mouth. In this study, for clarity, the route of respiration was limited by blocking either the mouth (or the nose) with surgical tape. Further, a cylinder was attached to the nose (or the mouth) for stable temperature measurement at the aperture. These constraints may have influenced the results. In particular, the attachment of the cylinder to the mouth constrained the deglutition of saliva, which could have influenced the sensation of dryness at the mouth or throat, and thus the temperature at the mouth aperture. Therefore, in future work, it is necessary to observe the differences between the natural and constrained states employed in this experiment.
4.2.2. Setting of temperature for exposure

This study focuses on clarifying the influence of humidity on the sensation of dryness; therefore, the baseline of the temperature of the experimental room was set at a relatively high level (29 °C) to enable a more distinct difference in evaporation rate. This is because a higher temperature enhances evaporation rate from a wet surface (the surface of the inner wall of the airway would always be wet with a humidity of 100% RH.) The thermal sensation was not recorded in these experiments, and the conditions would not have been thermally neutral. In this paper, the sensation of dryness was targeted, and it was assumed that the sensation of dryness was independent from the thermal sensation. In the same way, this was assumed implicitly in the other previous studies (Toftum et al. 1998, Karaki et al. 2004) by asking thermal sensation and the sensation of perceived humidity or dryness independently. However, this assumption should be validated in the future work.

4.2.3. Measurement of temperature of exhaled air

In this study, the temperature was measured at the aperture of the nose or mouth. A measurement of humidity would quantify the moisture state of the airway. However, the response of a humidity sensor is generally much slower than that of a temperature sensor. Therefore, temperature measurement was conducted to detect the behavior of the 4-6 s respiration cycle in this study.

4.2.4. Number of subjects

Four subjects were employed for this experiment. For Experiment 1 (change in vapor pressure), the difference in air temperatures of exhaled air between the humidity conditions was clear, and the difference in sensations of dryness for various parts of the airway for respiration through both the nose and mouth was amply...
clear. On the other hand, in Experiment 2 (change in temperature), the difference in temperature of exhaled air between temperature conditions was determined. However, the difference in humidity was not very clear. This should be reconfirmed by employing many more subjects for the experiment.

4.2.5. Order of exposure to hygrothermal conditions

The protocol of experiments in this paper, the order of conditions of humidity and temperature of ambient air were kept constant. To exclude the influence of order perfectly, it is necessary to confirm the results by conducting the experiments with random order of conditions, although the influence of the previous conditions could not be deemed significant, as shown in Figures 11 and 12. If the influence of order of exposure conditions of humidity or temperature had been significant, the sensation of dryness should have shown strong transient characteristics. In other words, the subjects’ ratings of sensation should have changed for each condition. However, the ratings did not show such strong transient characteristics though they fluctuated to some extent.

4.2.6. Sensation of dryness and thirst at airway

The sensation was surveyed as “dryness”. The sensation of “thirst” can occur in the oral cavity, pharynx, and larynx (mouth and throat). However, here, “thirst” was not targeted or considered. Some persons do not discriminate between “thirst” and “dry.” It would be meaningful to clarify the relationship between them.

4.2.7. Influence of season

The experiments were conducted in the winter season. The purpose of this study is to clarify the influence of short-time-exposure to a certain hygrothermal condition of indoor air. However, the influence of long-time-exposure on the results should be clarified in further study.

Figure 11. Sensation of dryness of each subject as a time series during Experiment 1. (a) Nose aperture, (b) Oral cavity
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4.3. Possibility of modeling

The sensation of dryness is a psychological variable. It is desirable to be able to predict the sensation of dryness to optimally control the indoor thermal environment. If the mechanism of the occurrence of the sensation of dryness in terms of the moisture state of the airway is clarified, that will lead to the prediction of the sensation of dryness. In this study, the relationship between evaporation rate in the airway and the sensation of dryness was suggested from the experimental results. This shows the possibility of the modeling and is thought to be a meaningful step.

5. Conclusions

This experimental study observed the sensation of dryness in the airway and the hygrothermal state of the airway in four subjects under different conditions of humidity and temperature generated in an artificial climate chamber. The experiments revealed that the exhaled air temperature was lower in the case of low humidity, which might be explained by the decrease in surface temperature in the airway as a result of inhalation of air with low humidity, accompanied by enhanced evaporation. At the same time, the experiments revealed that the sensations of dryness at the nose, mouth, and throat were more intense under the low-humidity conditions. These results suggest that the increase in the evaporation rate in the airway may have caused the sensation of dryness. On the other hand, upon changing the air temperature, the temperature of the exhaled air in the case of higher temperature was, of course, higher, and this resulted in higher surface temperature in the airway. This may have increased saturated vapor pressure on the surface in the airway, thereby enhancing evaporation rate. In addition, it was found that the sensation of dryness tended to be more intense for the high-temperature condition. The reason for this might be because the higher ambient temperature enhanced the evaporation rate in the airway. These findings should be confirmed by conducting similar experiments.

Figure 12. Sensation of dryness of each subject as a time series during Experiment 2. (a) Nose aperture, (b) Oral cavity
with a larger number of subjects and a randomly designed order of exposure to several conditions of air humidity and temperature, because only four subjects were employed and the order of the conditions for exposures was kept constant in this study. In addition to this confirmation, further directions of investigation include identifying the mechanism behind the sensation of dryness at the airway and the possibility of modeling and predicting this sensation based on thermal and environmental parameters, including temperature and humidity.

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