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Study on the Lower Limit of Indoor Humidity

Subject Experiments on Psychological Responses

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Abstract:

As a basis for determining the lower limit of acceptable humidity in an indoor environment, experiments were conducted for 25 subjects to assess the maximum expected sensations of dryness, discomfort based on humidity, and intolerance based on humidity, under conditions of 26°C and 10% RH. As results, distinct negative evaluations (dry, uncomfortable, or intolerable) were not obtained as the majority response; however, a small number of subjects declared distinct negative responses. In addition to the whole body evaluation, the sensations for individual body parts were collected and found to be more intense for the eyes, nose, throat, and lips than for the other body parts. Significant differences between the genders were not found. For 8 of the subjects, similar experiments under a condition of 30% RH were conducted, and the difference between two humidity conditions was clearer for discomfort and intolerance than for dryness. The results suggest that the evaluation of the specific individuals who respond intensely, the consideration of intense responses for a specific part of the body, and the careful selection of an evaluation word for a psychological response might be effective to link this study to the determination of the lower limit of indoor humidity.

Keywords: humidity, acceptable range, sensation of dryness, discomfort, subject experiment, body segment

Practical Implications:

The lowest humidity acceptable for humans has not been clarified.

Over-humidification in buildings under a low-humidity climate causes risks of increase in energy consumption and moisture damage.

This study aims to clarify the lowest humidity acceptable for humans for the optimum control of indoor humidity.

In this study, the psychological responses related to humidity or dryness were collected in subject experiments for extremely low humidity as the first step to determine the humidity limit.

This study provides knowledge on how to collect responses to determine the humidity limit.

1. Introduction

Guidelines for indoor thermal environments to secure the thermal comfort of occupants have been established based on evaluations of thermal sensations. The effects of humidity on thermal comfort have been examined based on quantifications via skin diffusion and perspiration in the heat balance of the human body. They are also considered in thermal indices such as the predicted mean vote (PMV) and the standardized new effective temperature (SET*). However, the non-thermal psychological responses related to moisture or humidity, such as dryness and wetness, remain largely unexplored.[1] According to a survey, 70% of office workers have experienced discomfort due to dryness.[2] In ASHRAE Standard 55, the existence of a lower limit of humidity due to non-thermal factors, such as the dryness of skin and eyes and the inflammation of mucous membranes, is suggested. However, the specific thermal environment conditions required to avoid the negative influences on humans is unclear, and the lower humidity limit is not shown in the acceptable range in ASHRAE Standard 55.

Conversely, the lower limit values of humidity are defined in environmental health management standards in several countries. In low humidity environments, which often emerge during the winter in many countries, rooms are often actively humidified to meet the standards. In general, excessive humidification causes condensation and mold and increases energy consumption; therefore, humidification should be minimized. To achieve reasonable indoor environmental control, a low humidity limit needs to be established quantitatively.

In determining the lower limit of the indoor humidity, there are various factors, such as psycho-physiological responses, as well as prevention of static electricity, infection by viruses, and moisture damage to buildings. An appropriate strategy is to determine the lower limit for each factor and then address the findings comprehensively to determine indoor humidity guidelines. In this study, we focus on the human psychological response to low humidity conditions.

Experimental studies focusing on human responses to various humidity conditions are less frequent than those focusing on temperature conditions. Fang et al.[3] conducted experiments in which the temperature and humidity conditions were changed in terms of perceived air quality; however they did not focus on drying. Toftum et al. [4] examined the upper limit of humidity in terms of feeling of skin wetness. Several experiments have been conducted in which subjects were exposed to low humidity conditions, and the degree of dryness was assessed. Andersen et al.[5] exposed eight young male subjects in a room to a temperature of 23°C and a relative humidity of 9% for 78 hr (after an exposure to a relative humidity of 50% for approximately 27 hours), and a questionnaire concerning the humidity was continuously conducted; there was a large fluctuation in the reported value, and the relationship to the humidity condition was not clear. In addition, Sunwoo et al.[6] conducted an experiment in which the subjects were exposed to a temperature of 25°C and a relative humidity of 10%, 30%, or 50% to examine the difference in the dryness feeling between humidity conditions; however significant differences were not observed. Wyon et al.[7] conducted experiments at 22°C with 5% RH, 15% RH, 25% RH, and 35% RH, and stated that subjective discomfort does not increase very much even at low humidity. Tsutsumi et al.[8] conducted experiments with relative humidity levels of 30%, 40%, 50%, and 70% under a SET* of 25.2°C and showed that no significant difference was found in the reported values of the dryness feeling. These studies did not show that exposure to low humidity produces noticeable dryness.

In these studies, dry–wet (humid) scales (sensation of dryness) were used. Although, no human mechanism for perceiving humidity has been found,[9] this does not mean that humans do not respond to low humidity. Decreased moisture content in a specific part of the body would cause some sensation that is different from the normal state, which is then reported as dryness, discomfort, and, sometimes, intolerance to humidity.[2] Evaluation of the degree of dryness, discomfort, and intolerance experienced based on humidity may help to quantify the effects of low humidity on humans. It is further expected that collecting quantitative ratings of sensation of sensation of dryness, discomfort, and intolerance will provide useful information from which we may establish the lower limit of acceptable humidity, which has not been clarified yet.

Moreover, identifying body parts that trigger sensations of dryness, discomfort, and intolerance is important in clarifying human responses to humidity. Responses of individual body parts, such as the eyes, airway, and skin have been studied.[10-15] However, the relationships between these responses and psychological responses have not been identified.

In determining the lower humidity limit, a reasonable method is to expose subjects to various temperature and humidity combinations to determine a threshold of acceptability for humans. This operates on the assumption that clear dryness, discomfort, or intolerance should be detected at the lowest humidity level.

Accordingly, in this study, experiments were conducted to expose 25 subjects (13 male and 12 female subjects) to a low humidity environment with a relative humidity of 10% to confirm the maximum expected response on the dry side for sensations across the whole body and for several body parts. The feeling of dryness as well as the discomfort and intolerance regarding the humidity were measured, and the intensity of the feeling was studied. Moreover, the difference between the genders was checked for each measured sensation. Moreover, 8 of the subjects were also exposed to 30% RH to compare these results with the results of the case in which 10% RH was used. This was done to explore the possibilities to determine the limit of humidity.

2. Methods

2.1 Experiment

There were 25 subjects, 13 males and 12 females, participating in the experiments from January to March 2018 (Table 1). After staying in an anteroom (19–23 °C, relative humidity 20–40%) for 20 min, the subjects stayed in a climate chamber set at 26°C and 10% RH for 2 hr and 40 min (Figure 1). Reports on sensations of dryness, discomfort based on humidity, and intolerance based on humidity were made at 5 min intervals using the visual analog scale shown in Figure 2. In addition, the subjects were instructed to express verbally if they felt any discomfort or trouble in any parts of their bodies. The reports started 40 min after entering the artificial climate chamber and continued for the following 2 hr. Drinking fluids was not permitted during the experiment. Subjects wore a designated clothing ensemble (0.65 clo) and were instructed to remain sedentary during the experiment. The temperature, humidity (Espec RS-14) and wind speed (Kanomax 6543) were continuously measured and recorded automatically. Of the subjects shown in Table 1, five male and three female subjects also participated in an experiment under conditions of 30% RH from February to March 2018 using the same experimental method. The ethics committee of Kobe University approved the experimental plan, and experiments were conducted after obtaining informed consent from the subjects based on the Helsinki Declaration.

2.2 Statistical analysis

In this study, the psychological responses of the subjects to low humidity are considered to be the main output from the experiments. The Mann-Whitney *U*-test was applied to compare gender differences and differences in responses to exposure to the two humidity conditions. P values <0.05 were considered to be statistically significant. All statistical analyses were conducted using Bell Curve for Excel (version 3.20).

3. Results of the experiment

3.1 Exposure to 10% relative humidity

The temperature inside the artificial climate chamber was 26.5 ± 0.1°C, the relative humidity was 8.4 ± 0.5%, and the wind speed was 0.31 ± 0.04 m/s. In the following, the declared sensations are shown as an average of the data obtained during the final 2 hr of each experiment.

The average value of the sensation of dryness for 2 hr was approximately 0 (neutral) to +1 (slightly dry) for the whole body and each body part (Figure 3). This is not a strong sensation of dryness. However, 40% of the reports gave values larger than 0, which means that the sensations were on the dry side for the whole body, eyes, nose, throat, and lips (Figure 4). Reports on the dry side were less numerous for the mouth and skin (face, hands, and other skin). For the face, reports on the dry side reached 30%. However, for the hands and other parts of the skin, reports were as low as 10%. This tendency for each body part was also true for the average values in Figure 3. For the mouth and hands, responses on the "wet" side were higher than those for the other body parts. The influence of saliva in the mouth, or moisture accumulation in the palm, likely accounts for this result.

Responses of +3 (very dry) were 1.4% for the whole body and 0.0–3.4 % for all parts of the body. Responses of +2 (dry) were 13.3% for the whole body and 0.5–19.1% for all parts of the body. The highest rate for the responses of +2 was for the lips (19.1%), followed by the throat (14.6%), eyes (11.2%), and nose (9.9%). For the skin (face, hands, and other area of skin), 58.7%, 51.1%, and 83.8%, respectively, of the responses were "neutral" (Figure 4).

Next, the results of the sensation of dryness are shown for each individual subject (Figure 5). For the whole body, most of the subjects gave responses on the dry side (>0). Subjects m2, m11, and m13 declared stronger sensations of dryness compared to other subjects, while subjects m1 and f10 consistently declared “neutral” sensations.

For each body part, for all 25 subjects, the declared values on average for 2 hr exceeded +1 (slightly dry) for 4 subjects for the eyes, for 4 subjects for the nose, for 8 subjects for the throat, and for 7 subjects for the lips. Subject m1, who consistently declared “neutral” sensations for the whole body, made a declaration of approximately +1 for the lips, while subject m11, who had a large dryness declaration value for the whole body, made a declaration of approximately 0 for the throat. Even though individual differences can be seen, as a whole, the sensation of dryness for each body part tended to the dry side when the sensation for the whole body was on the dry side.

The average discomfort value regarding the humidity for 2 hr was approximately −1 (slightly uncomfortable) to 0 (neutral) for the whole body and each part (Figure 6). This is not a strong discomfort sensation, even though more than 30% of the reports were values smaller than 0, which means that the sensations were on the uncomfortable side for the whole body, eyes, nose, throat, and lips (Figure 7). For the mouth and face, 20–25% of the reports were on the uncomfortable side, and for the hands and other skin, less than 10% of the reports were on the uncomfortable side.

Responses of −3 (very uncomfortable) were 0.3% for the whole body and 0.0–1.4 % for all parts of the body. Responses of −2 (uncomfortable) were 3.4% for the whole body and 1.3–11.3% for all parts of the body; the highest rate was for the throat (11.3%), followed by the lips (10.5%), eyes (9.2%), mouth (3.7%), and nose (3.4%). For the skin (face, hands, and other area of skin), 48.2%, 59.6%, and 72.0%, respectively, of the responses were “neutral” (Figure 7).

Next, the results of the discomfort based on humidity are shown for individual subjects (Figure 8). For the whole body, only 9 of the 25 subjects gave responses on the uncomfortable side (<0). Subjects m2, m11, and m13 who declared stronger dryness, again declared stronger discomfort than the other subjects, even though the values were approximately −1 (slightly uncomfortable). Conversely, most of the subjects gave responses on the uncomfortable side answer for the eye, throat, and lips.

With regard to the intolerance based on humidity, 95% of the answers were “tolerable” or “rather tolerable” (Figure 9). Declarations of “intolerable” were rare (f5 and f9 gave this response only once). Nearly 60% of m11’s answers were “rather intolerable.” This subject reported a relatively strong declaration of dryness and discomfort due to humidity.

In terms of sensations of dryness and discomfort in response to humidity, the gender differences were not statistically significant for the whole body or individual body parts, except for discomfort at the skin on humidity (Table 2, Figure 4, and Figure 7). The female subjects declared a greater comfort at the skin, although the intensity of responses was not strong. The male subjects declared a slightly dryer sensation and greater discomfort in the whole body, nose and lips, whereas the female subjects declared these sensations in the throat and mouth. Additionally, no significant differences were observed for intolerance to humidity. As a whole, no significant gender differences were found in psychological responses related to humidity or dryness.

3.2 Exposure to 30% relative humidity

The temperature inside the artificial climate chamber was 25.9 ± 0.2°C, the relative humidity was 24.4 ± 0.9%, and the wind speed was 0.37 ± 0.03 m/s. In the following, the results of exposure to 30% RH, compared to those to 10% RH, are given for the same subjects.

Regarding the sensation of dryness for the whole body under the 30% RH condition, subjects f5 and f8 reported significantly smaller values, i.e., they gave votes more toward the moist side than under the 10% RH condition. However, for the other subjects, the difference was not clear. For subject m7, the responses were on the dryer side under the 30% RH conditions (Figure 10).

However, most subjects reporting whole body discomfort were more inclined toward the comfortable side under the 30% RH condition than under the 10% RH condition (Figure 11).

For declarations of intolerance for the whole body, the responses shifted to the "tolerable" side under the 30% RH condition, except the answers given by subject m7, whose responses concerning the dryness were on the dryer side and whose responses concerning discomfort were on the uncomfortable side (Figure 12).

For the reported values for individual body parts, approximately half of the subjects gave responses more toward the moist side under the 30% RH condition compared to under the 10% condition for the sensation of dryness. Conversely, most of the subjects gave responses on the more comfortable side under the 30% conditions. That is, the tendency for the difference between the 10% RH and 30% RH conditions is the same as the results for the whole body (Table 3).

Contrary to theory, subject m7 declared dryer responses under the 30% RH condition than under the 10% condition for the whole body, and for each body part, and gave uncomfortable ratings under the 30% condition for the eyes, throat, mouth, lips, face, and hands. The experiments under the 10% condition and the experiment under the 30% condition were conducted on different days, and the subject's conditions may have been different (subject m2 had just returned from a tropical country the day before participating in the 30% experiment).

4. Discussion

4.1 Non-steady processes of the psychological response

Tsutsumi et al.[8] reported the sensations of dryness of 12 young male and female subjects exposed to relative humidity conditions of 30%, 40%, 50%, and 60% (SET* 25.2°C) for 3 hr just after exposure to 30°C and 70% RH conditions for 15 min. Significant differences were not found between humidity conditions. In the transient state over 3 hr, the declarations changed gradually from "neutral" to “slightly dry” on average for all the subjects.

Sunwoo et al.[6] exposed eight young male subjects to three conditions in 25°C, 10% RH, 30% RH and 50% RH for 2 hr and recorded the sensation of dryness for the nose, throat, eyes, face and hands. The results for the dryness for the nose, on average, for all subjects was between “neutral” and “slightly dry,” and over 2 hr, this sensation became gradually stronger approaching “slightly dry.” However, over the course of the 2 hr, the sensation of dryness weakened once and then again became stronger. Further, a large fluctuation with time was found. Judging from the standard deviation, some subjects might have answered “dry” or “neutral,” even though it is not clear from the description in their paper.

In this paper, the averages of the reported values concerning the sensation of dryness and discomfort/intolerance based on humidity obtained over a period of 2 hr were studied. Before entering the artificial climate chamber, the humidity was higher. Therefore, the observed situation in this paper follows a stepwise drop in the humidity. Even though the fluctuations with time in the reported values were large, there is an indistinct tendency for the reported values to have peak values on the dry, uncomfortable, and intolerable side approximately 30–90 min after entering the low humidity environment. It is necessary to examine this transient response.

4.2 Ambient temperature settings and thermal sensations

Although it is necessary to conduct experiments at various temperatures and to study the effects of temperature on the results, this study focused on obtaining data under a very low humidity at a specific temperature. In many past studies on dryness, thermal sensation and dryness sensation were often treated independently,[6-8] and the same policy was adopted in this paper. Hence in this study, the ambient air temperature was fixed to 26°C, which is within the common range of temperatures for a normal office environment in winter,[16] albeit near the upper limit of that range.

In the experiments of this study, thermal sensation was collected based on the similar scale as PMV (+3: hot, +2: warm, +1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, -3: cold). Results indicated that thermal sensation was almost neutral for 25 subjects (-0.28 ± 0.69) at 10% RH and for 8 subjects (-0.16 ± 0.71) under 30% RH under the clothing of 0.65 clo. The influence of thermal sensation on dryness sensation would have been minimal.

4.3 Declared psychological characteristics of dryness

The correlation between the whole body reported values was examined for all the experimental data under a condition of 10% RH. For the sensation of dryness, when the reported values were larger than 0 (on the "dry" side), 51% of the reported values were on the discomfort side (less than 0), while when the reported values on the discomfort side less than 0 (on the "uncomfortable" side), 87% of the reported values were larger than 0 (on the "dry" side) for all the subjects (Figure 13). When subjects do report discomfort based on humidity, it is usually on the dry side; this may indicate that discomfort is more suitable for psychological evaluations of low humidity than a sense of dryness because it directly expresses a bodily sensation. As shown in Figure 13, these tendencies were common for males and females. Even though the responses of the male subjects had a tendency to show higher linkage between dryness and discomfort to humidity, the difference between the responses of the genders was not significant. Although showing clear differences between the psychological responses of the genders to low humidity is difficult, several differences were suggested not only in Figure 13 but also in the discussions in subsection 3.1. To confirm the gender difference, conducting additional experiments with a large number of subjects is necessary.

Table 4 shows the questionnaire results obtained during the experiments described in this paper using the words expressed by subjects when they felt discomfort or trouble with respect to their bodies, in order to investigate the possibility of a psychological evaluation of low humidity with words other than “dry,” “uncomfortable,” and “intolerable.” Common responses included “it is dry (kawaiteiru),” “rustle (kasakasa),” “tingling (hirihiri),” “aching (itai),” “whistling (suusuu),” and “crumbly (pasapasa).” These expressions, which include onomatopoeia, are more direct descriptions of the sensation than “dry.”

In most previous studies, only the average of multiple subjects was reported. However, the difference between subjects is large even under the same environmental conditions. Moreover, the responses of most subjects were close to “neutral” and were subtle; therefore, averaging is not necessarily a good strategy. To determine the mechanism of the occurrence of a sensation of dryness or its transient response, picking subjects who respond sensitively to low humidity would be a better strategy.

To examine individual differences in the declarations of dryness, discomfort based on humidity, and intolerance based on humidity, it is necessary to find a factor that correlates well with the sensitivity to low humidity. In this study, according to the questionnaire given to the subjects, several factors such as gender, wearing contact lenses, self-reporting trouble with eyes/nose/throat/skin, and smoking habits, were investigated. However, it was impossible to determine a good factor to explain the individual differences in responses. Further investigations are, therefore, necessary.

5. Conclusions

Using experiments in which 25 male and female subjects participated, it was shown that psychological responses of dryness, discomfort based on humidity, and intolerance based on humidity were weak even under extremely low humidity (26°C and 10 % RH) when averaged data were considered of all the subjects. However, a few subjects declared distinct negative responses. When the comparison between the whole and local body sensations was considered, the psychological responses were more distinct for the eyes, nose, throat, and lips than for the mouth, face, hands, and other skin areas. Significant gender differences were not found in the characteristics of the declaration of dryness, discomfort based on humidity, and intolerance based on humidity. From the experiments with exposure to 30% RH conditions for 8 subjects, it was shown that the declarations of discomfort and intolerance clearly decreased compared to the experiments with exposure to 10% RH conditions, while results concerning the declaration of dryness were not clearly explained.

Because the average of the psychological responses of multiple subjects did not show a distinct negative response even for extremely low humidity, to determine the lower limit of acceptable humidity, one suggestion was to use the subtle differences of averaged data as the majority. The other was to use the responses of a small number of specific subjects who showed distinct responses in the dry/uncomfortable/intolerant reports. In addition, the suggestion was made that an evaluation word should be aptly selected: “uncomfortable” or “intolerant” were better than “dry” to determine this condition. Moreover, words expressing discomfort or trouble declared by the subjects, such as “rustle,” “aching,” or “crumbly” as well as several words that conveyed onomatopoeia, could be a prospective candidates to clarify the responses.

The overarching goal of this study is to determine the lowest humidity acceptable for humans for the optimum control of indoor humidity. In this paper, which represents the first step towards this goal, the strongest expected response to low humidity by exposing human subjects to the lowest possible humidity attainable in living environments was examined at a specific temperature. Future experiments at different (higher) humidity levels and temperatures and with greater numbers of subjects are required in order to determine the lower limits of acceptable humidity at various temperatures.

Individual differences will always exist in human physiological and psychological data. In this study as a whole, the responses to low humidity were not distinct. However, there were a small number of subjects who responded distinctly to lower humidity levels through sensations in certain regions of the body. It is important to identify the parameters that explain the occurrence of such distinct responses. Potential explanatory variables for the obtained in this study were gender, age, the use of contact lenses, self-reported trouble with the eyes/nose/throat/skin, and smoking habits, although the number of the subjects who responded distinctly was too small to identify a definitive variable to explain the sensation of dryness. Another area requiring future research might be the elucidation of individual parameters that explain the occurrence of distinct psychological responses to low humidity. This could be achieved through an extensive study, which could also clarify the mechanisms underlying the sensation of dryness and perhaps to pinpoint a certain group of people who require countermeasures for low humidity.

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Table 1 Subject profiles.

	Attendance		Profiles of subjects				
	10%rh	30%rh	Gender	Age	Contact lens	Diseases (based on self assessment)	Smoking habit
m1	X		Male	23	Soft Contact Lens		
m2	X		Male	24			Yes
m3	X		Male	23			
m4	X	X	Male	22			
m5	X	X	Male	24		Dry eye	
m6	X		Male	23			Yes
m7	X	X	Male	21	Soft Contact Lens	Allergy to pollen	Yes
m8	X	X	Male	23	Soft Contact Lens		
m9	X	X	Male	21	Soft Contact Lens	Chronic rhinitis	
m10	X		Male	22			
m11	X		Male	21			Yes
m12	X		Male	46			
m13	X		Male	37			
f1	X		Female	23	Soft Contact Lens		
f2	X		Female	22	Soft Contact Lens		
f3	X		Female	24			
f4	X		Female	22	Soft Contact Lens		
f5	X	X	Female	23	Soft Contact Lens		
f6	X		Female	22			
f7	X	X	Female	21	Soft Contact Lens	Allergic rhinitis	
f8	X	X	Female	23			
f9	X		Female	21	Soft Contact Lens	Dry eye	
f10	X		Female	37	Soft Contact Lens		
f11	X		Female	40	Soft Contact Lens (Only left eye)	Dry eye, Allergy to pollen	
f12	X		Female	47	Soft Contact Lens		

Table 2 Average declared values of sensations of dryness and discomfort based on humidity for each subject (10% RH). Gender differences were analyzed using Mann-Whitney *U*-test with a 95% confidence interval (* $p < 0.05$).

Note: m, all the male subjects; f, all the female subjects.

		male													female												m	f	Gender difference
		m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11	m12	m13	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12			
Vote for sensation of dryness	whole body	0.0	1.4	0.7	0.9	-0.1	0.3	0.3	0.1	0.7	-0.2	1.6	0.0	2.2	0.5	0.5	0.6	0.9	0.0	0.7	-0.4	1.0	0.3	0.0	-0.2	0.4	0.6	0.4	n.s.
	eye	0.1	1.3	0.5	1.0	0.1	0.8	-0.2	0.6	0.2	0.2	1.3	0.2	1.3	1.8	1.0	0.8	0.5	0.4	0.5	0.2	0.4	-0.3	0.5	-0.3	0.1	0.6	0.5	n.s.
	nose	0.3	1.3	0.1	0.6	1.0	0.1	0.8	0.0	0.8	0.0	2.0	0.2	1.4	0.4	0.6	1.0	0.7	0.0	1.7	-1.2	1.0	-0.3	0.0	-0.5	0.6	0.6	0.3	n.s.
	throat	0.0	0.3	1.2	0.5	0.5	1.4	0.0	-0.1	0.7	0.6	0.3	0.1	-2.0	1.8	1.0	0.1	1.5	0.2	1.3	1.4	1.2	1.5	0.2	-0.6	0.6	0.3	0.9	n.s.
	mouth	0.0	-0.9	1.2	0.0	0.1	0.8	0.1	-1.0	0.3	0.4	-0.4	-0.1	-2.0	-0.2	0.2	0.2	1.0	0.7	-0.8	-0.2	0.8	1.2	0.2	-0.7	0.7	-0.1	0.3	n.s.
	lip	1.0	0.2	1.0	0.0	0.1	0.7	1.1	0.8	1.0	1.1	1.0	0.3	1.9	1.3	2.3	0.4	1.4	0.4	0.0	0.1	1.6	0.8	0.0	-0.5	0.2	0.8	0.7	n.s.
	face	0.0	0.7	0.4	1.0	0.4	0.0	0.2	0.2	0.1	0.4	0.3	-0.1	0.4	1.0	0.1	0.6	0.8	0.0	0.4	0.3	1.0	0.0	0.0	-0.4	0.2	0.3	0.3	n.s.
	hand	-0.4	0.8	0.0	-0.5	-0.2	0.2	0.1	-0.7	0.0	-0.6	-0.1	0.0	0.2	0.0	0.4	-0.6	-0.6	0.0	-0.1	-1.0	0.4	0.6	0.3	-0.8	-0.4	-0.1	-0.2	n.s.
	skin	0.0	0.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	-0.2	0.2	0.3	-0.1	0.0	0.4	0.0	0.0	0.1	0.0	-0.8	0.0	0.0	0.0	n.s.
Vote for discomfort on humidity	whole body	0.0	-0.8	-0.5	-0.4	0.4	0.1	0.9	1.4	-0.5	0.8	-1.2	0.8	-1.1	-0.4	-0.1	0.2	0.4	0.3	1.0	0.4	-0.4	0.1	0.0	0.2	1.1	0.0	0.2	n.s.
	eye	0.0	-1.5	-0.4	-1.4	-0.2	-0.2	0.6	-0.5	-0.3	-0.1	-1.3	0.5	-0.9	-1.5	-0.5	-0.8	-0.6	0.0	0.8	0.1	-0.1	0.5	-0.5	0.3	0.3	-0.4	-0.1	n.s.
	nose	0.0	0.2	0.0	-0.9	1.3	-0.1	-0.4	1.7	-0.8	1.5	-1.8	0.5	-1.1	-0.3	-0.1	-0.4	-0.8	0.2	1.4	-0.3	0.8	0.2	0.0	0.2	0.4	0.0	0.1	n.s.
	throat	0.0	-0.6	-1.2	-0.2	-0.3	-0.9	0.2	1.0	-0.7	-0.6	-0.5	0.8	0.0	-1.8	-0.8	-0.2	-1.2	-0.4	-1.2	-1.1	-0.9	-0.8	-0.2	0.6	-0.1	-0.2	-0.7	n.s.
	mouth	0.0	1.0	-1.0	0.0	0.1	-0.5	0.3	1.6	0.0	-0.7	0.2	0.6	0.0	0.0	-0.2	-0.3	-1.0	-0.4	0.6	0.2	-0.8	-1.0	-0.2	0.8	0.0	0.1	-0.2	n.s.
	lip	0.0	-0.2	-1.0	0.1	0.2	-0.3	-0.6	-0.6	-0.7	-1.0	-1.3	0.1	-1.4	-1.4	-1.4	-0.5	-1.1	-0.1	-0.2	0.4	-1.2	-0.7	0.0	1.1	1.1	-0.5	-0.3	n.s.
	face	0.0	-0.7	-0.2	-1.1	1.5	0.1	0.7	1.4	0.0	-0.2	-0.1	0.4	-0.2	-0.9	-0.1	0.2	-0.4	0.2	0.1	0.7	-0.8	0.8	-0.3	1.0	0.8	0.1	0.1	n.s.
	hand	0.0	-0.5	0.0	0.2	0.2	0.1	0.7	0.2	0.0	0.8	0.2	0.2	0.0	-0.2	0.0	0.7	0.2	0.2	1.4	1.0	0.0	-0.2	0.0	1.1	1.0	0.2	0.4	n.s.
	skin	0.0	-0.4	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0	0.3	0.1	0.0	-0.4	0.0	-0.2	0.4	0.1	0.2	1.3	0.7	-1.0	0.0	0.0	1.1	1.3	0.0	0.3	*

Table 3 Average declared values of the sensation of dryness and discomfort based on humidity (10% RH versus 30% RH).

		young male										young female					
		4		5		7		8		9		5		7		8	
		10%	30%	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%
Vote for sensation of dryness	whole body	0.9	0.7	-0.1	0.1	0.3	1.9	0.1	0.1	0.7	0.8	0.0	-0.5	-0.4	-0.4	1.0	0.5
	eye	1.0	0.4	0.1	-0.2	-0.2	1.2	0.6	0.5	0.2	0.1	0.4	-0.7	0.2	-0.1	0.4	-0.1
	nose	0.6	1.1	1.0	0.7	0.8	2.4	0.0	1.0	0.8	0.7	0.0	-0.7	-1.2	-1.0	1.0	-0.2
	throat	0.5	0.8	0.5	0.8	0.0	2.2	-0.1	-1.8	0.7	0.8	0.2	-0.4	1.4	-0.4	1.2	0.1
	mouth	0.0	0.6	0.1	0.2	0.1	2.1	-1.0	-1.7	0.3	0.0	0.7	-0.3	-0.2	-0.2	0.8	0.3
	lip	0.0	0.0	0.1	0.0	1.1	1.6	0.8	0.9	1.0	0.0	0.4	-0.6	0.1	-0.2	1.6	0.9
	face	1.0	0.6	0.4	0.4	0.2	1.1	0.2	0.3	0.1	0.1	0.0	-0.6	0.3	0.0	1.0	0.2
	hand	-0.5	0.0	-0.2	0.0	0.1	0.3	-0.7	-1.5	0.0	0.0	0.0	-0.7	-1.0	-0.7	0.4	-0.1
	skin	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.7	0.0	0.0	0.0	0.0
Vote for discomfort on humidity	whole body	-0.4	0.2	0.4	0.8	0.9	1.0	1.4	1.8	-0.5	-0.2	0.3	1.0	0.4	0.9	-0.4	-0.3
	eye	-1.4	-0.6	-0.2	0.4	0.6	-0.6	-0.5	0.6	-0.3	-0.1	0.0	0.6	0.1	0.6	-0.1	0.2
	nose	-0.9	-1.2	1.3	1.3	-0.4	1.6	1.7	2.6	-0.8	-0.7	0.2	1.0	-0.3	-0.6	0.8	-0.3
	throat	-0.2	-0.4	-0.3	-0.3	0.2	-1.8	1.0	2.0	-0.7	-0.7	-0.4	0.8	-1.1	0.4	-0.9	-0.4
	mouth	0.0	-0.2	0.1	-0.1	0.3	-1.6	1.6	1.9	0.0	0.0	-0.4	0.8	0.2	0.3	-0.8	-0.6
	lip	0.1	0.1	0.2	0.5	-0.6	-1.4	-0.6	0.2	-0.7	0.0	-0.1	1.0	0.4	0.6	-1.2	-0.9
	face	-1.1	-1.0	1.5	1.4	0.7	0.1	1.4	1.7	0.0	0.0	0.2	1.0	0.7	0.3	-0.8	-0.1
	hand	0.2	0.4	0.2	1.0	0.7	0.5	0.2	0.2	0.0	0.0	0.2	1.0	1.0	0.1	0.0	0.0
	skin	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.2	-0.1	0.7	0.0	-1.0	0.0

Table 4 Words expressing discomfort or trouble declared by subjects and the number of subjects who declared these words for each body part.

words declared (original expression by Japanese subjects)	whole body	eyes	nose	throat	mouth	Lips	face	hands	other skin
be dry (kawaiteiru)	5	5	1	6	3	4	3	1	3
rustle (kasakasa)	3	1	2	1	1	6	4	3	1
itchy (kayui)	5	4	1				4		3
tingle (hirihiri)	2	1	1	1		3	3	3	
wet, sweaty, moist(shittori, aseppoi, shimeppoi)	3				1			7	2
aching (itai)		3	2	3		1			
want to drink water (mizuwonomitai)				2	7				
irritating (igaiga)				9					
whistling(suusuu)		1	6	1					
on the verge of tears (namidagadesou)		7							
cold, chilly (samui, tsumetai)	4							1	1
crumbly (pasapasa)		1		2		2		1	
blinking often (mabatakigaooi)		5							
strained (hatteiru)							5		
stuffed (tsumaru)			4						
smooth (saratto)	1							1	1
feel windy (kazewokanjiru)		2							1
crispy, cracked (paripari, pakipaki)						2	1		
nose is running (hanamizugaderu)			3						
clinging (haritsuku)				3					
want to close eyes (mewotojitai)		2							
feel pungent (tsu-ntosuru)			2						
feel breath passing (ikigatoru)			2						
sticky (betatsuku, nebaneba)					2				

There are 20 more expressions that were declared by only one subject; these are omitted here.

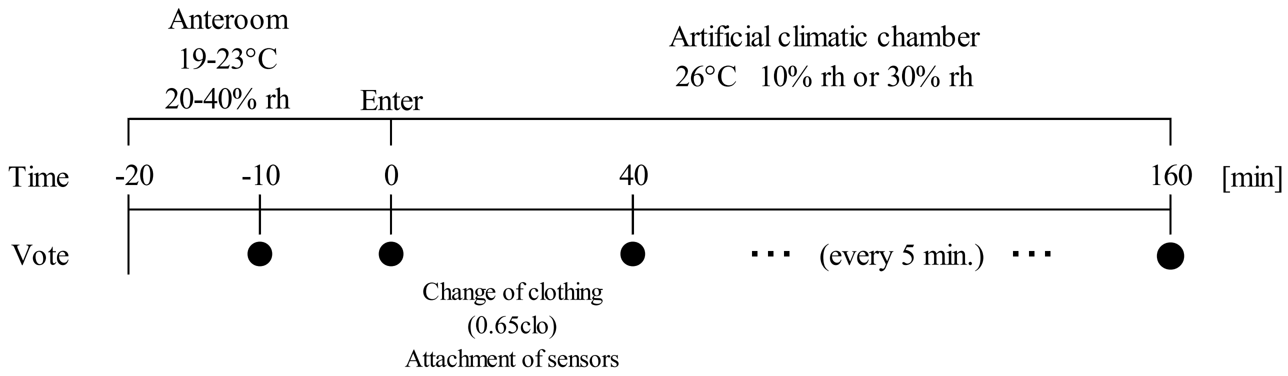


Figure 1 Experimental protocol.

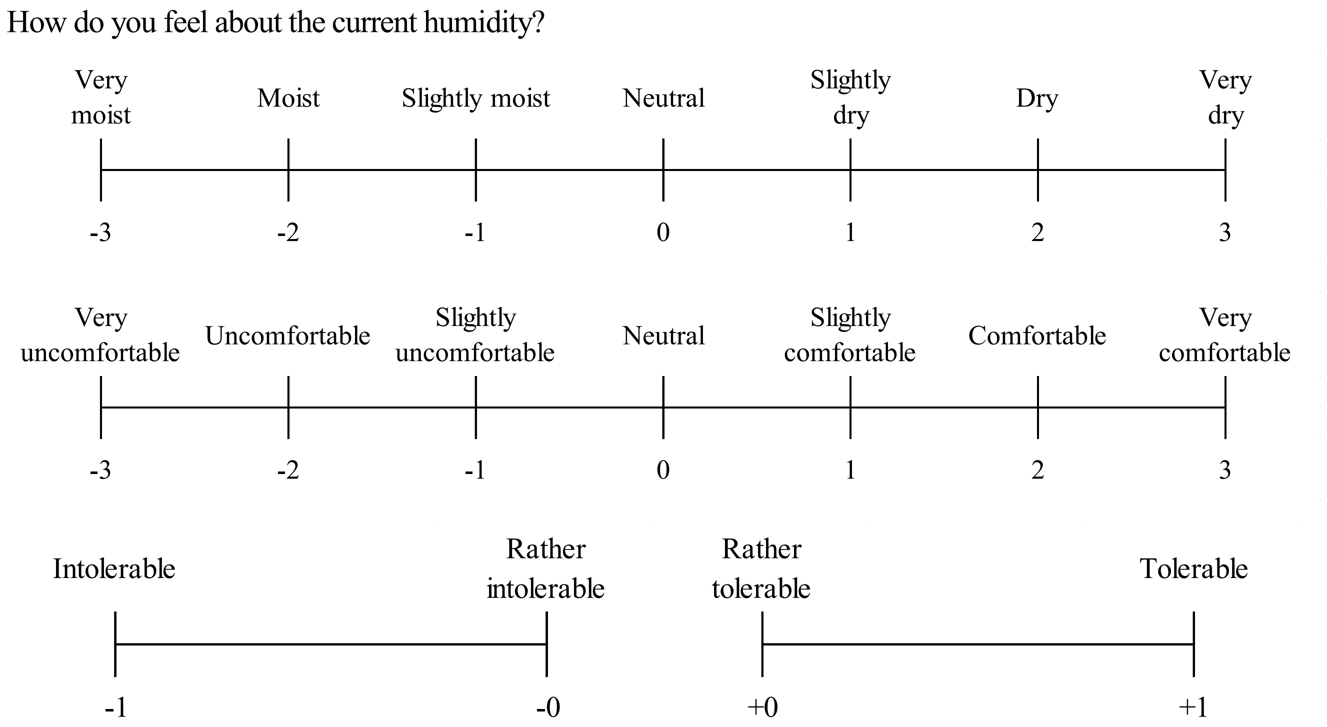


Figure 2 Scales of the sensation of dryness, discomfort based on humidity, and intolerance based on humidity (originally in Japanese). Scales of the sensation of dryness and the discomfort based on humidity were used for the whole body and local body parts (eyes, nose, throat, mouth, lips, face, hands, other skin), and the scale for intolerance based on humidity was used for the whole body. For the first two scales, the subjects were instructed to answer “neutral” when they felt neither “dry” nor “moist”, or neither “comfortable” nor “uncomfortable”, respectively.

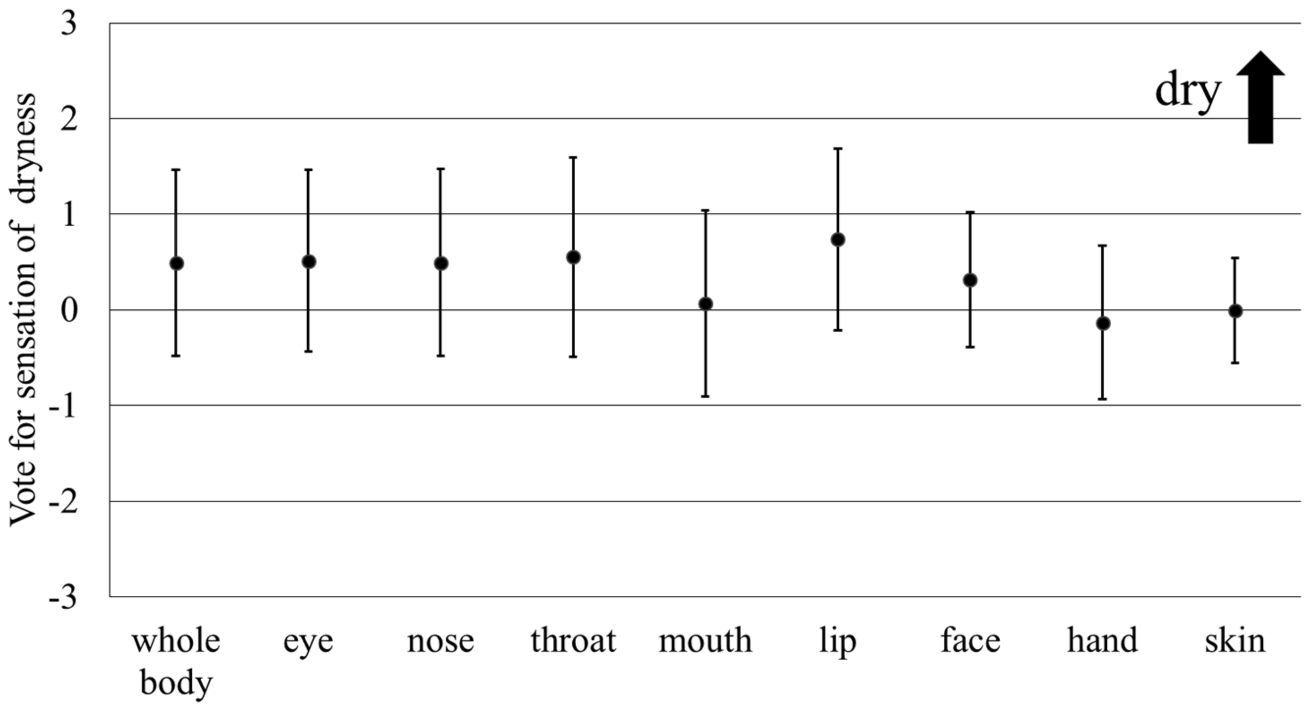


Figure 3 Average and standard deviation of the values of the sensation of dryness (all subjects, 10% RH).

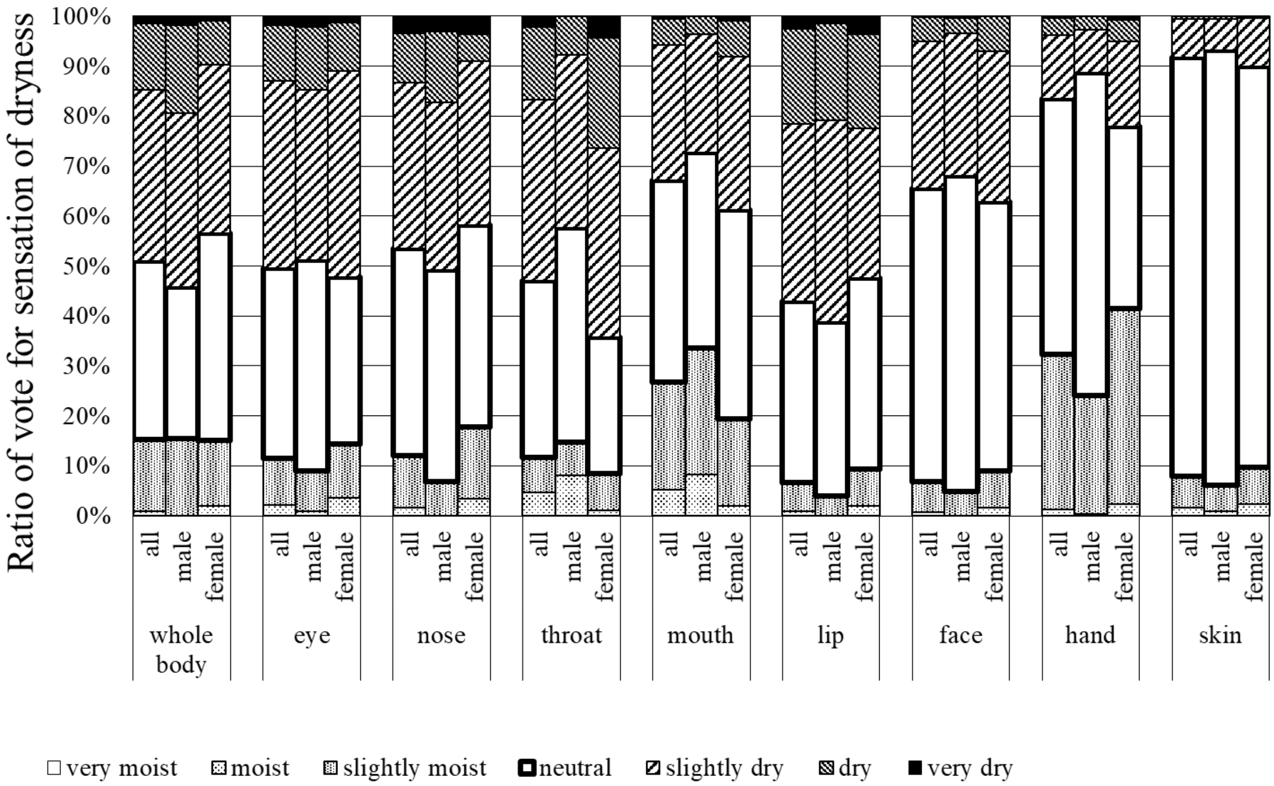


Figure 4 Ratio of each category for the declaration of the sensation of dryness (all subjects, by gender, 10% RH).

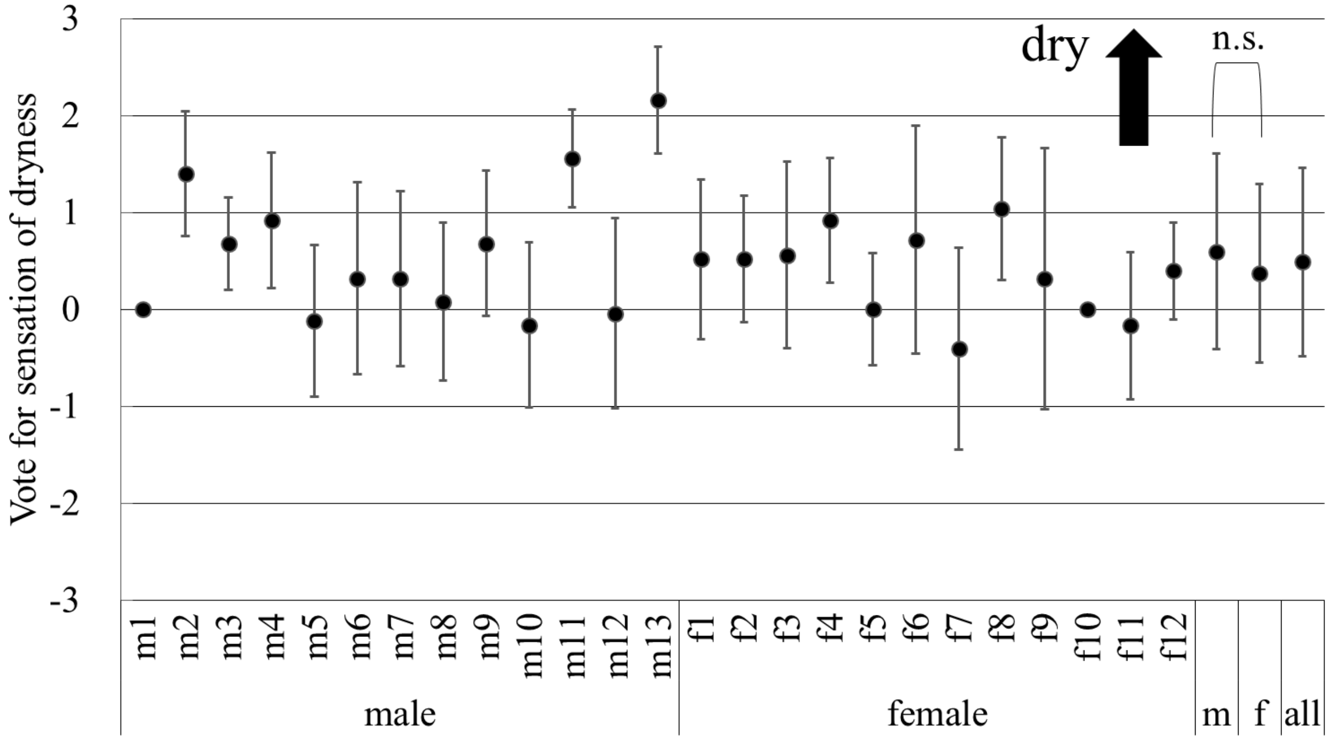


Figure 5 Average and standard deviation of the values of the sensation of dryness for the whole body for each subject (10% RH). Gender differences were analyzed using Mann-Whitney *U*-test with a 95% confidence interval.

Note: m, all the male subjects; f, all the female subjects; all, all the subjects.

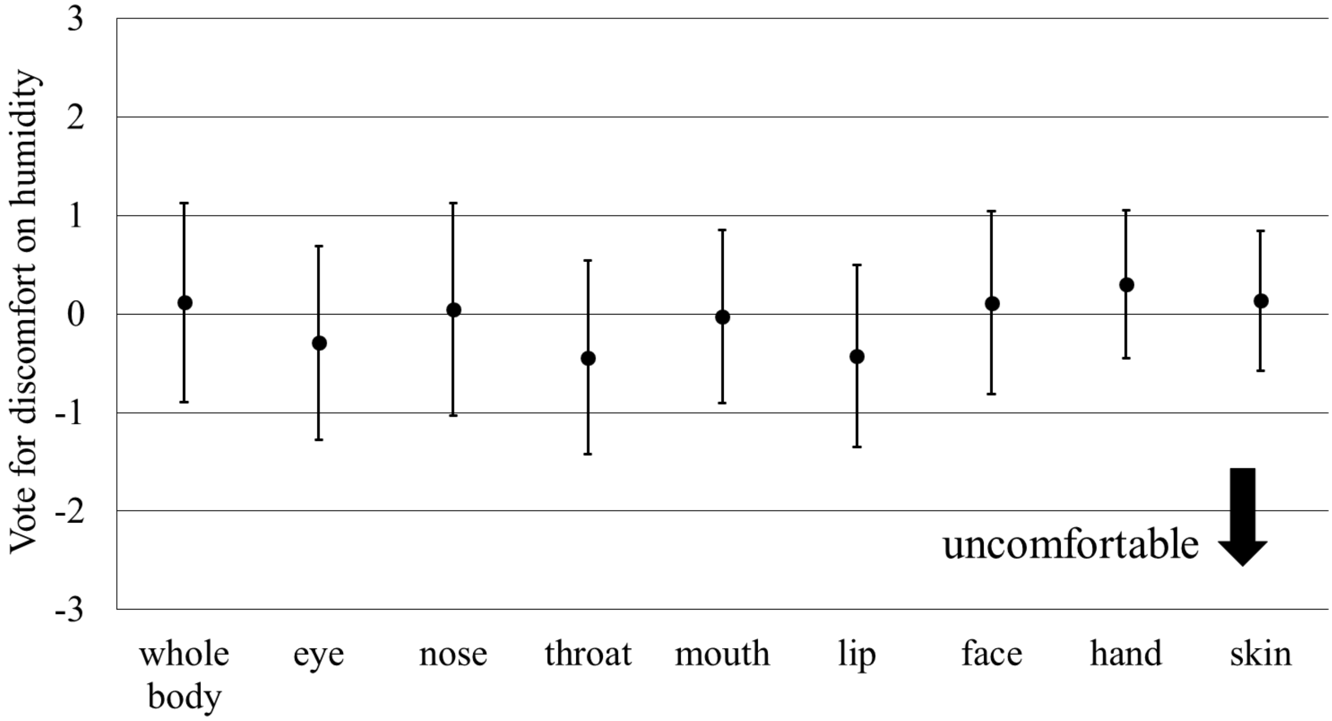


Figure 6 Average and standard deviation of the values of the declaration of discomfort based on humidity (all subjects, 10% RH).

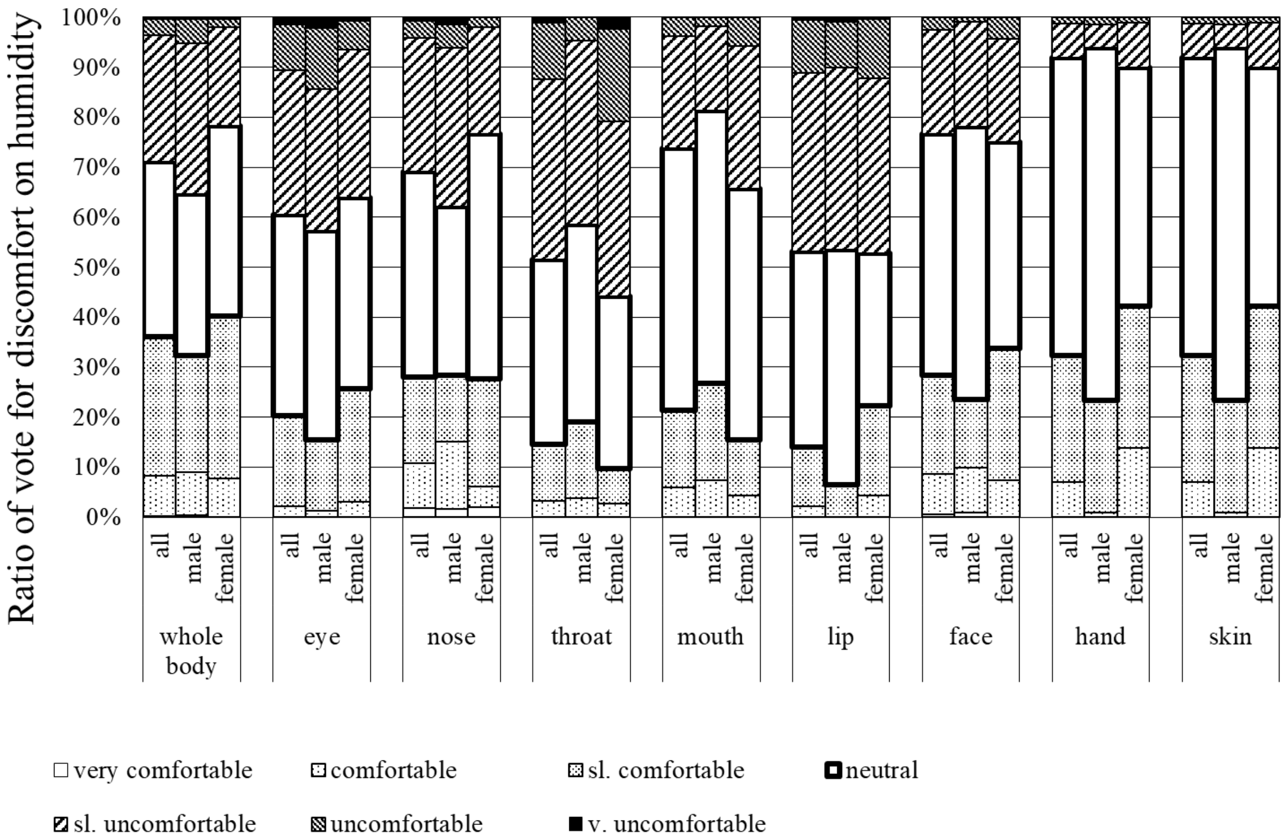


Figure 7 Ratio of each category for the declaration of discomfort based on humidity (all subjects, by gender, 10% RH).

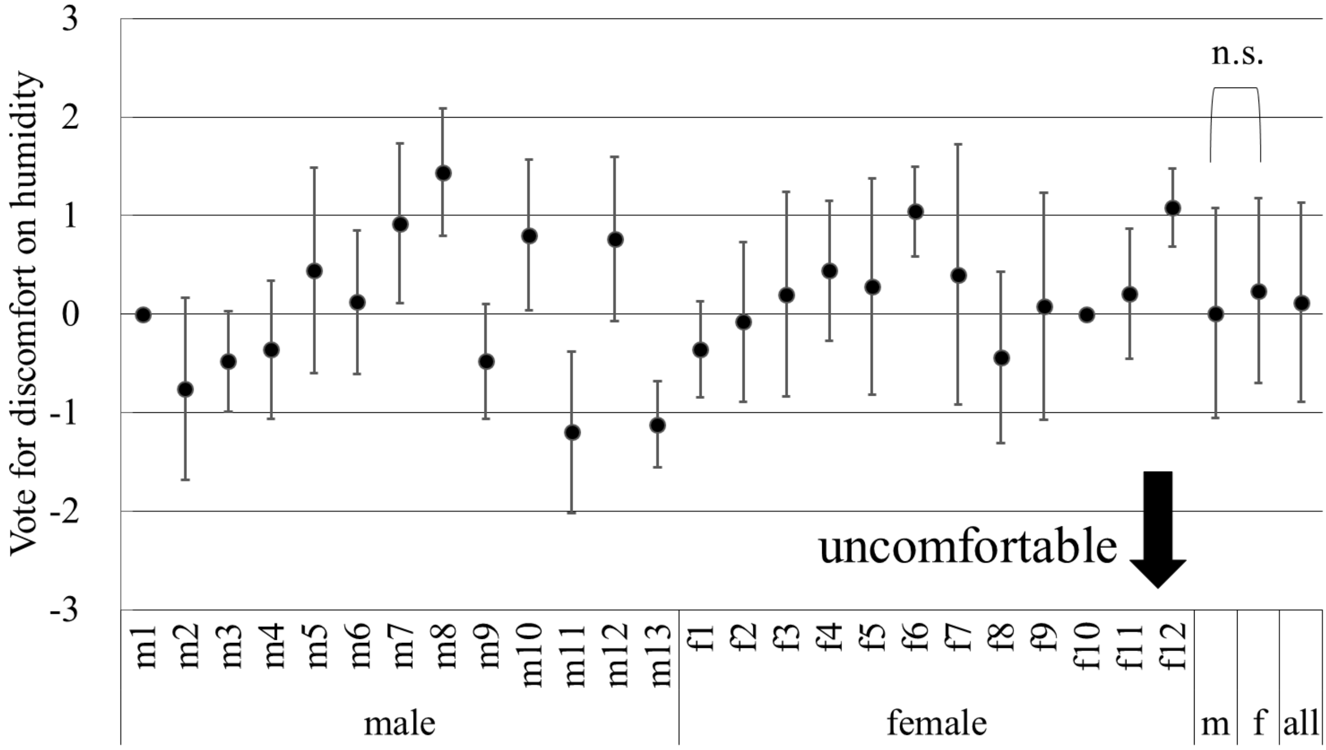


Figure 8 Average and standard deviation of the values of the declaration of discomfort based on humidity for the whole body for each subject (10% RH). Gender differences were analyzed using Mann-Whitney *U*-test with a 95% confidence interval.

Note: m, all the male subjects; f, all the female subjects; all, all the subjects.

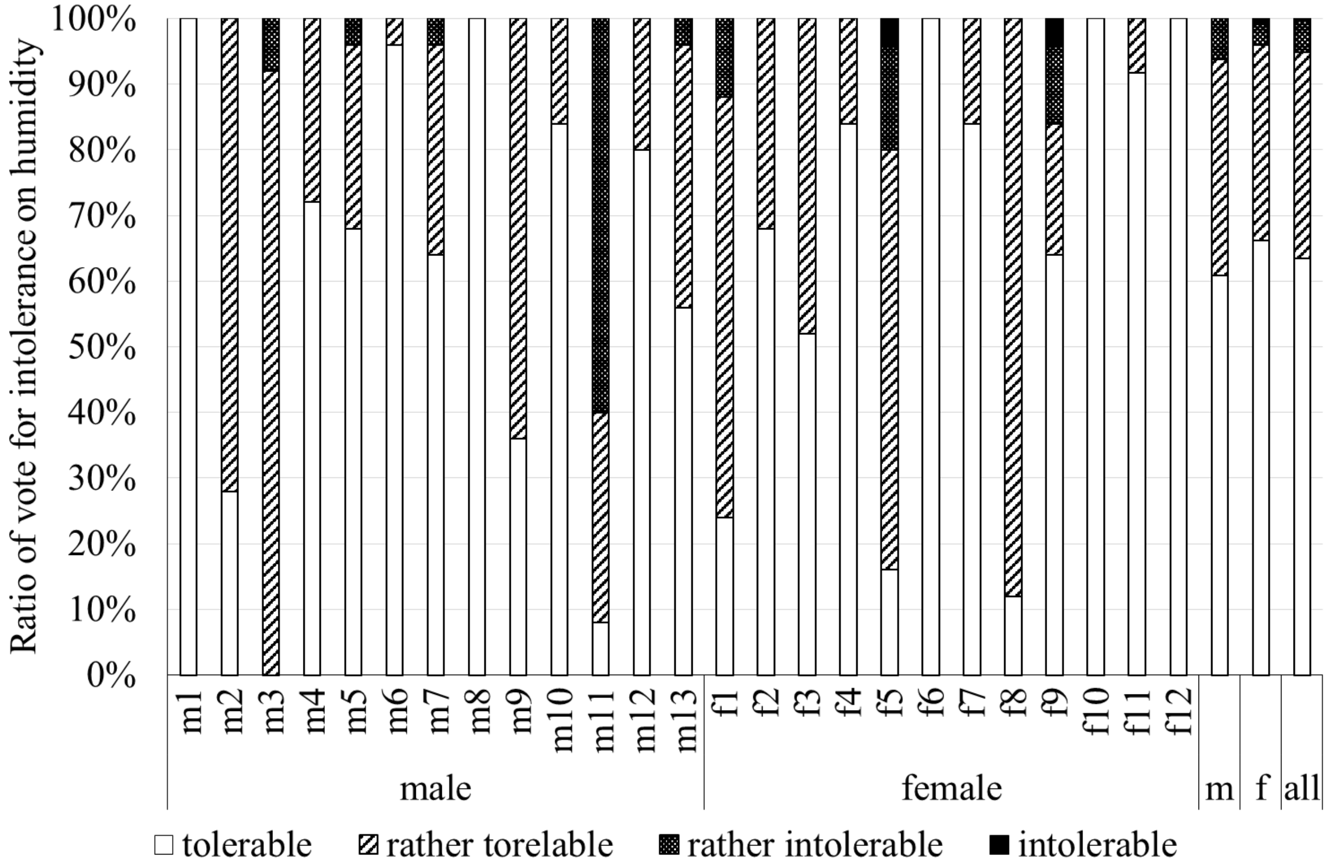


Figure 9 Ratio of each category for the declaration of intolerance based on humidity (all subjects, by gender, 10% RH).
Note: m, all the male subjects; f, all the female subjects; all, all the subjects.

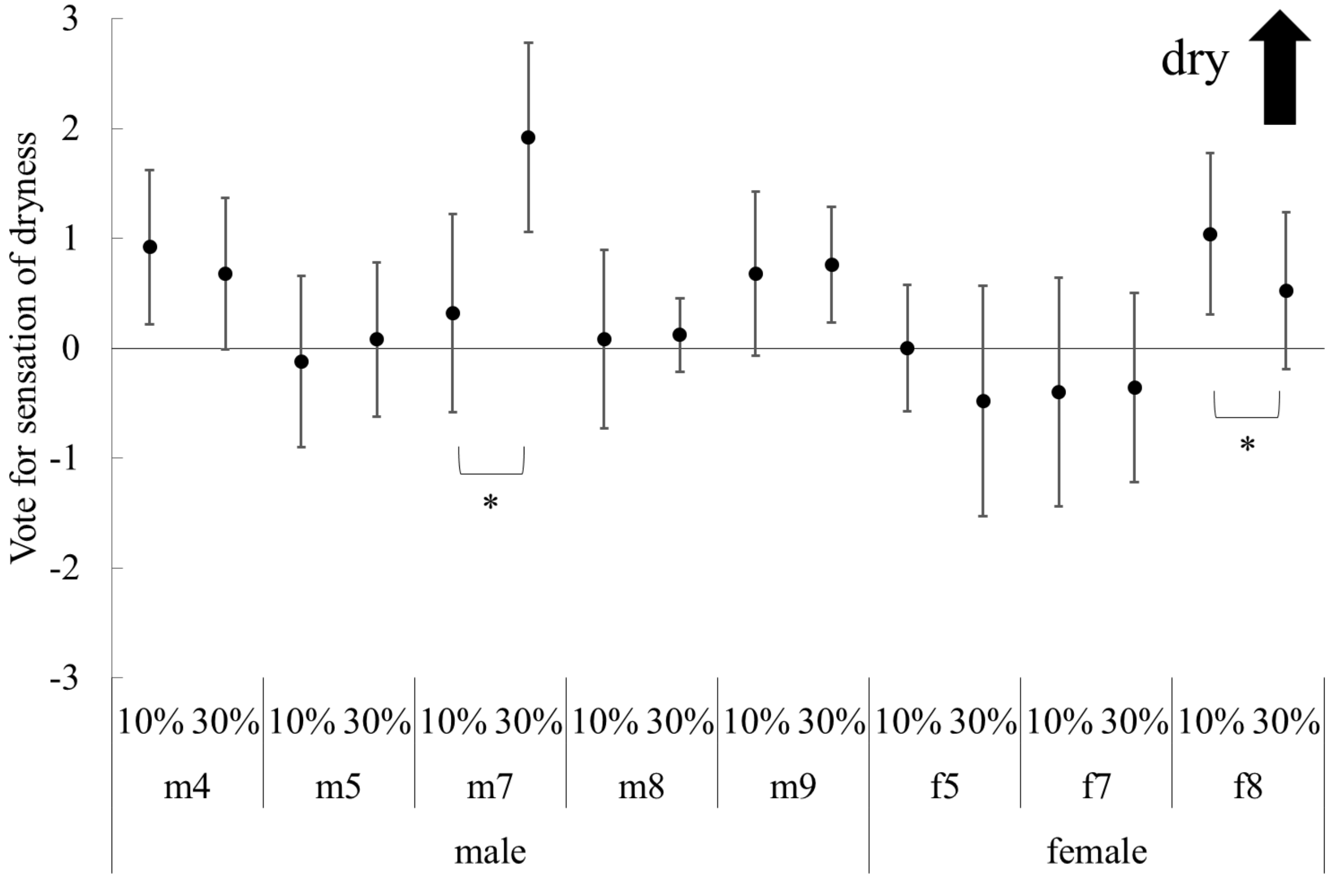


Figure 10 Average and standard deviation of the values of the sensation of dryness for the whole body (eight subjects): Conditions under 10% RH and 30% RH were compared, and differences were analyzed using Mann-Whitney *U*-test with a 95% confidence interval (* $p < 0.05$).

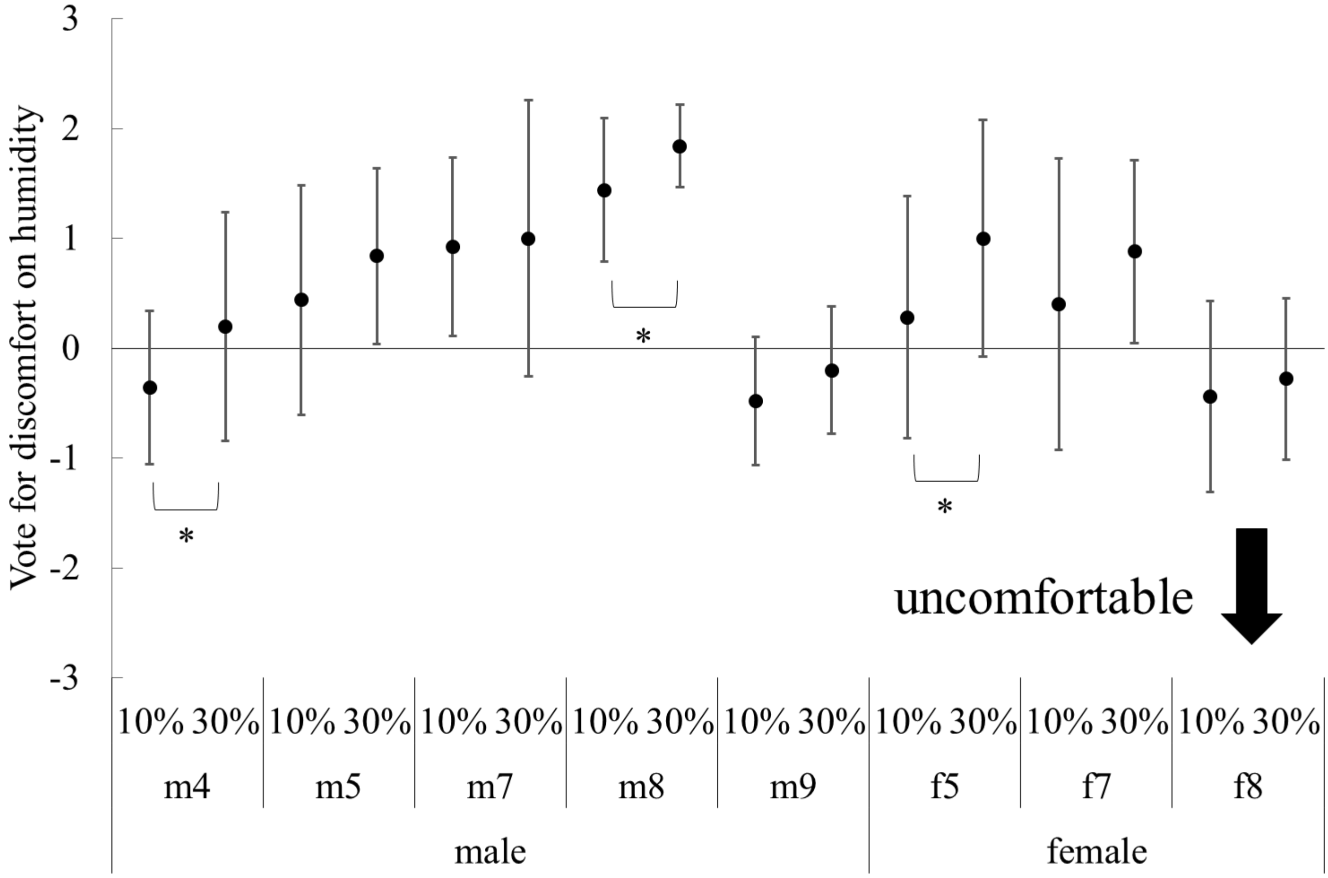


Figure 11 Average and standard deviation of the values of the declaration of discomfort based on humidity for the whole body (eight subjects): Conditions under 10% RH and 30% RH were compared, and differences were analyzed using Mann-Whitney *U*-test with a 95% confidence interval (* $p < 0.05$).

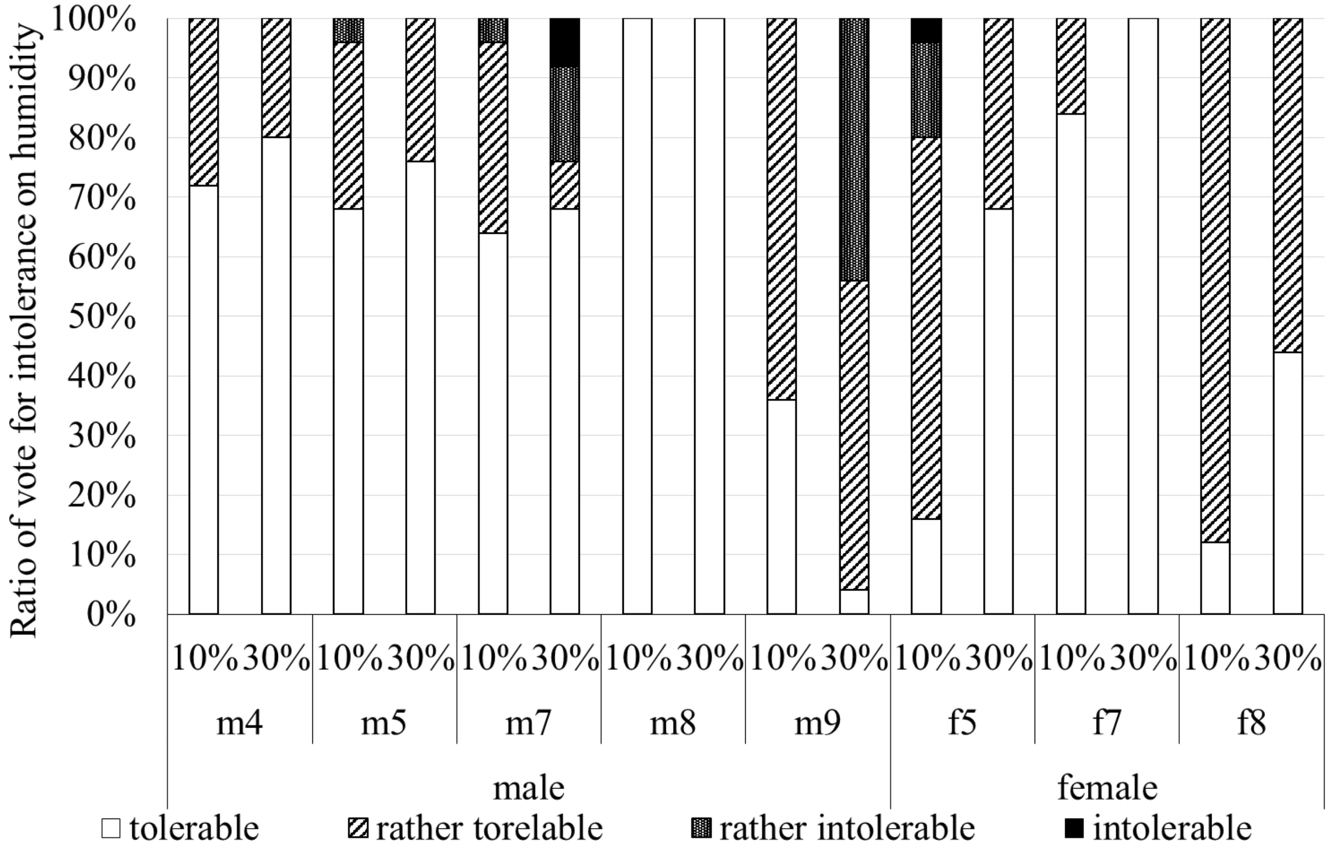
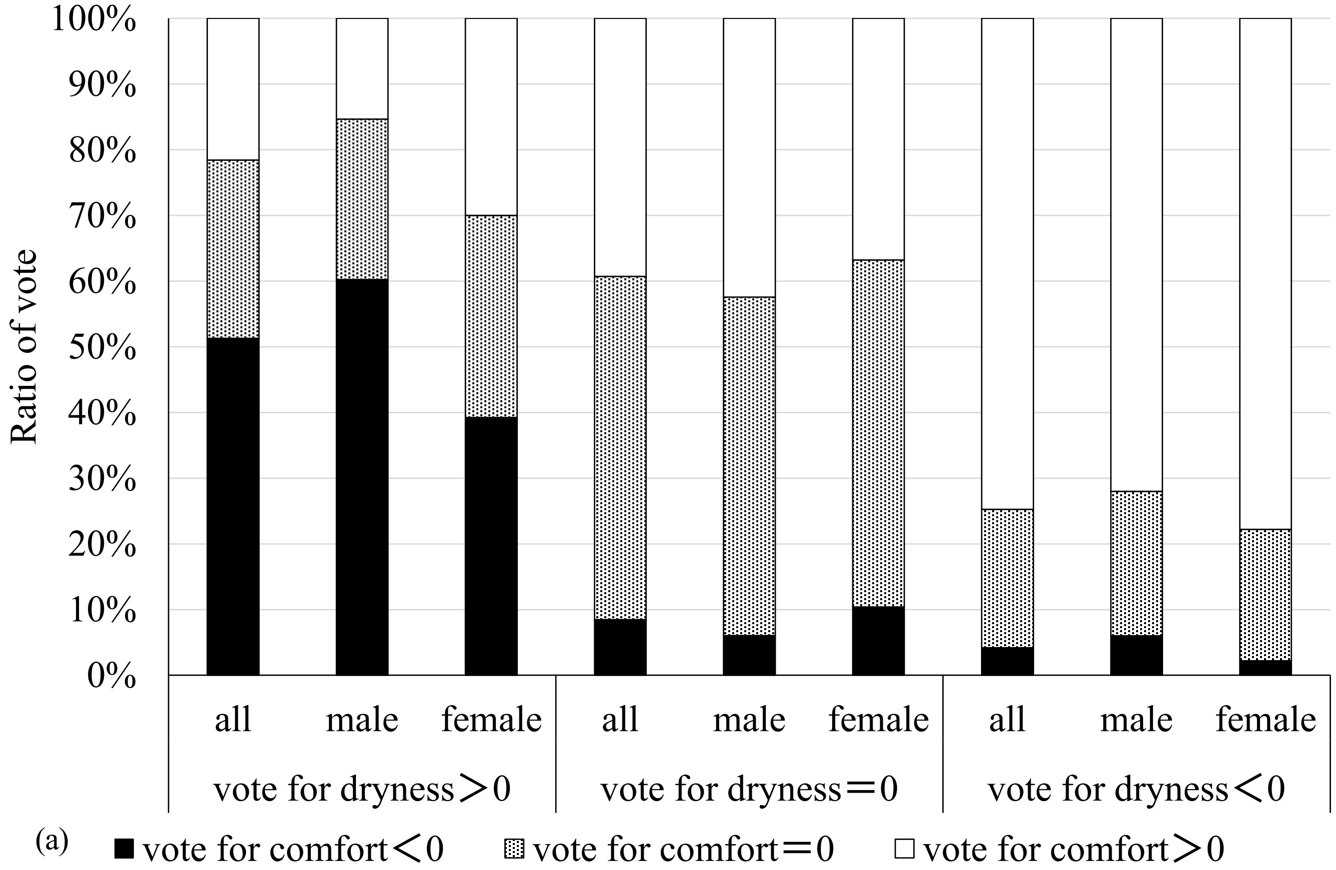


Figure 12 Ratio of each category on the declaration of intolerance based on humidity for the whole body (eight subjects, 10% RH versus 30% RH).



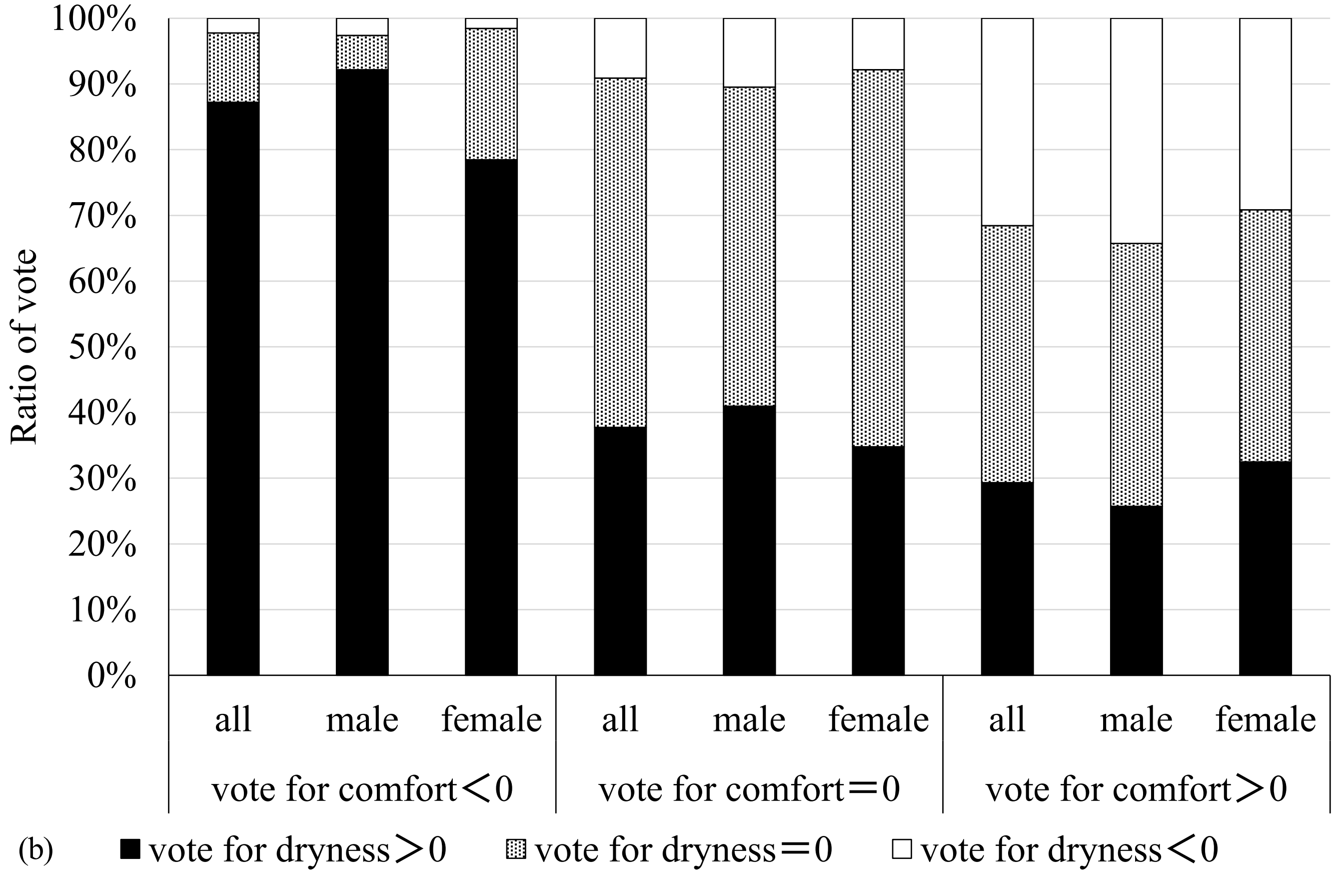


Figure 13 Cross-tabulation of the sensation of dryness and discomfort based on humidity for the whole body (10% RH). (a) The vertical axis is the percentage of votes for comfort, (b) The vertical axis is the percentage of votes for dryness. (All the subjects are considered: N = 25; male: N = 13; female: N = 12)