Title

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Publication Date
1995-09-25

Peer reviewed

The Effects of High-level Air Humidity on Subjective Perception of Comfort

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Abstract

There has been considerable discussion of what the maximum allowable relative humidity (RH) should be in occupied spaces. ASHRAE Standard 55, 'Thermal environmental conditions for human occupancy', has had three different maximum limits in the last 10 years. The mechanism by which high levels of humidity affect comfort is not yet fully understood. To determine what humidity levels are acceptable, a literature review and laboratory tests were carried out. This paper examines how human subjects evaluated comfort level and comfort acceptability under a range of high humidities, while holding their thermal heat balance constant. Human subjects were tested in a controlled environment chamber configured to resemble a modern office with typical furniture and partitions. Wearing informal office attire, the subjects imitated a series of different activities while being exposed to constant thermal conditions with relative humidities in the range from 50% up to 80%. The temperature setpoints were along the new effective temperature (ET^*) line at 26.1 °C. By subjective and physical measurements, the study attempted to explore the relationship of subjective comfort and humidity around the upper boundary of comfort zone specified in ANSI/ASHRAE Standard 55-1992.

1. Introduction

The definition of acceptable thermal environmental conditions for human occupancy plays an important role in affecting both energy use in buildings and the strategies that could be practised to achieve those conditions. In the 1981 version of ASHRAE Standard 55, the upper humidity limit was set at the constant dew point line of 16.7°C [1]. In 1992, ANSI/ASHRAE Standard 55 set an upper limit of 60% relative humidity (RH) in defining conditions for human thermal comfort [2]. Both limits were largely based on mold growth considerations. The latter RH limit was lower than that specified in the previous version of Standard 55 under most temperatures within the comfort zone, thus substantially affecting the applicability of ventilative and evaporative cooling technologies, as well as the design and operation of all HVAC systems. This limit was challenged and in Addendum 55a to ANSI/ASHRAE Standard 55-1992, it was acknowledged that the comfort standard should not use nonthermal environmental factors for definition, and that the comfort zone boundary at high humidity should be defined by comfort criteria instead of health associated considerations [3]. As a result, 60% RH limit line was replaced by two wet bulb temperature (WBT) lines to define the upper boundaries of the comfort zone for summer (WBT = 20°C) and winter (WBT = 18°C) in Addendum 55a to Standard 55-92. These lines were to approximate the loci of equal skin wettedness (20%) under summer and winter clothing. However, the changes are not yet fully supported by comfort studies and are worthy of examination. In terms of human comfort at high humidity levels, questions remain in defining the acceptable humidity limit. To explore what humidity

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Proceedings of the Second International Symposium on HVAC, 25-7 September 1995, pp. 81-91

levels are acceptable, laboratory tests were carried out to investigate how human subjects evaluate comfort level and comfort acceptability under a range of high humidities, while keeping their thermal heat balance constant. This paper presents some findings from the laboratory study about subjective perceptions for comfort at 1.2 met, the upper bound of primarily sedentary activities defined in the ANSI/ASHRAE comfort standard. For full details of the laboratory study, refer to Bauman et al. [4].

There have been many studies reported in the literature addressing the effect of humidity on comfort. Early in 1925, Yaglou et al. investigated the subjective thermal sensation at the various combinations of humidity and temperature, which led to the old effective temperature [5]. Fanger's comfort equation also denoted the effect of humidity on thermal sensation within the comfort zone [6]. Rohles et al. addressed in a study that the effect of temperature on thermal sensation was much more than that of RH [7]. McIntyre et al. examined the effect of humidity (20%, 50% and 70% RH) on comfort and found that the high level of humidity caused oppressive reactions from the subjects [8]. Tanabe et al. found that the subjects' comfort sensation was different at 80% RH from 70% RH or lower [9]. Berglund conducted subject tests under 27 combinations of air conditions and reported that thermal acceptability for the subjects with the same metabolic rate changed considerably with high levels of humidity at the same temperature [10]. His later study concluded that thermal acceptability decreases as the environmental temperature deviates from optimum comfort temperature and also decreases with the increasing humidity level [11]. Field measurements performed by de Dear et al. [12] and Busch [13, 14] in hot humid locations indicated that thermal requirements for indoor environments could be more warmer and more acceptable to the occupants than predicted by comfort models and standards based on midlatitude research. However, no explicit evidence about comfort can be found from the previous work to entirely support the upper limit of humidity level in the current ANSI/ASHRAE Standard 55 [2].

2. Objectives

The purpose of this paper is to examine the relationship between subjective comfort and humidity from 50% RH to 80% RH with the ET^* held at 26.1°C, representing the upper temperature boundary close to that of current comfort zone (where $ET^* \leq 26°C$) in Standard 55-1992 [2,3]. The experiments examined how human subjects assessed their comfort, humidity perception and acceptability under these conditions.

3. Methods

3.1. Overall approach

In this study, subjects were tested in a controlled environment chamber configured to resemble a modern office. Wearing informal office clothing, the subjects performed a preset series of different activities while being exposed to constant thermal conditions with RH ranging from 50% up to 80% at the ET^* of 26.1°C. In order to simulate light activities in real office work, a step-exercise routine representing the light activity level common in offices was employed, similar to that of a previous study [15].

To accomplish the objectives, we decided to test the conditions with RH from 50% through 80%, including the 60% specified in the original version of Standard 55-1992. Test condition setpoints are shown in Figure 1. Human subjects were tested in the chamber featuring office settings. The subjects were required to wear a long-sleeve shirt, long pants (but not jeans), and athletic socks. The ensemble was chosen to approximate the average clothing found in previous field studies of office environments [16,17], which resulted in the clothing insulation value (I_{cl}) of 0.6 *clo* (ASHRAE Standard summer ensembles in office building). In fact, there was an additional increment in the overall insulation from sitting on a padded chair [18], which has been conventionally neglected in the standard. An additional 0.26 *clo* was estimated for the chair using thermal manikin [4]. The metabolic rates were attained by doing a series of step-exercises under the researcher's instruction. For the first ninety minutes, the metabolic rate was prescribed to be 1.2 met as specified in ASHRAE Standard 55 [1,2,3].

The tests were conducted in summer time (May to August), during which the RH in the real outdoor environments was more likely to be high, thus was closer to the test conditions. Upon arrival at the chamber, each subject was provided with a low speed fluctuating fan [19] to supply circulating air for ten minutes. This was to create natural breezes in the chamber and counter the effect, if any, of possible sensation hysteresis on humidity perception or thermal sensation after they came into the chamber.

3.2. Controlled Environment Chamber

All the experiments were done in the Controlled Environmental Chamber (CEC) located at the University of California at Berkeley. Measuring 5.5 m × 5.5 m × 2.5 m, the CEC is a full-scale room with carpeted floor designed to represent a modern office space, while still allowing a high degree of control over the indoor thermal environment provided by a dedicated HVAC system. It has windows on two sides with glass temperature being held equal to the indoor air temperature throughout each experiment. More details are shown in Bauman et al. [20]. Partitions were used to divide the CEC into four parts with 3 subjects occupying the cubicles with outside views. The researcher occupied the fourth cubicle. Subjects' cubicles were furnished with conventional office desks and chairs with armrests, and an assortment of books and magazines. These were intended to create a real office-like atmosphere. The diffuser and the return inlet were located on the ceiling to produce a uniform interior temperature and humidity with relatively low air movement (air velocity ≤ 0.1m/s) in the occupied zone. The air temperature and RH were recorded every two minutes throughout the experiments.

3.3. Survey

In order to secure the information on people's response to the environmental conditions during the experiments, we designed a subjective questionnaire similar to that used in the study by Berglund [10], and distributed it to the subjects after they came in. The survey was composed of a background questionnaire, repeated questionnaire, and one page for open-ended comments. The background questionnaire asked questions about subject's background information including age, gender, height, weight, hours of exercise per week, and the importance of environmental characteristics about working place, such as air temperature, humidity, air movement, air quality, etc. During the test period, the subjects were periodically asked to answer questions on the repeated questionnaire about their thermal sensation, humidity perception, skin wettedness feeling, air movement perception and air quality. The open-ended comments were requested at the end of the test.

3.4. Test procedure

A total of 84 subjects were randomly arranged in four test conditions, with at least 20 subjects in each proposed condition. After they came into the chamber, the researcher explained to subjects about the procedure of their activities during the test, and then asked them to sit down and fill out the background survey. During the first 90 minutes, subjects were undergoing the 12-step exercise every 10 minutes. They concluded 3 repeated questionnaire in every 30 minutes, with each survey being scheduled right before the following exercise began.

4. Results and Discussion

4.1. Test condition

Table 1 shows the setpoints and measurements of test conditions with different combinations of air temperature and RH. The air temperature setpoint for each level of RH was calculated to give the same ET^* [21,22]. The measured values shown in Table 1 were the average RH and temperature for the first ninety minutes. The standard deviation of the temperature and RH was 0.4°C and 2.5%, respectively.

Table 1 Laboratory test conditions

Set Points		Measurement (90 min. average)		Subjects
RH (%)	Temperature(°C)	RH (%)	Temperature(°C)	Total
50	26.1	50.0	26.1	21
60	25.7	60.0	25.8	22
70	25.3	70.0	25.4	20
80	24.9	79.9	24.9	21

4.2. Subjective measurement analysis

Statistical analysis of the subjective measurements collected from surveys answered by the subjects are presented by employing ANOVA analysis, box-and-whisker plots, and Pearson's χ^2 tests. The analysis is repeated for the measured 7-point scale thermal sensation, comfort sensation, humidity perception, and skin wettedness feeling votes.

4.2.1 Thermal sensation

The subjects were asked to vote their thermal sensation on the ASHRAE thermal sensation's 7-point scale (*cold, cool, slightly cool, neutral, slightly warm, warm, hot*). ANOVA is used to test whether there was significant difference in the thermal sensation votes at the metabolic rate of 1.2 met across four RH levels with the same ET^*. Table 2 shows a *P-value* of 0.99, which indicates that the null-hypothesis assuming no significant difference among the *average* votes grouped by four RH levels holds. No significant difference in thermal sensation vote induced by high RH (up to 80% RH) can be found under the test conditions. This finding confirms results from Berglund's study [10] that no significant impact on subjective thermal sensation was caused by different humidity levels up to 80% RH.

Table 2 ANOVA for thermal sensation

	Sum of squares	Degrees of freedom	Mean square	F-ratio	*P-value*
Between RHs	0.103	3	0.034	0.045	0.99
Within RHs	60.837	80	0.760		

The box-and-whiskers plot (Figure 2) displays the distribution of thermal sensation votes classified by four humidity levels (50%, 60%, 70%, 80% RH). Grouped by the four different test conditions with RH ranging from 50% to 80%, the plot of the quantitative vote based on thermal sensation scale displays the percentile distribution within each category. In the plot, the horizontal line inside the box represents the 50th percentile (median), which splits the ordered batch of voting values in half. The horizontal borders of the box represent the 25th and 75th percentile, which respectively splits the remaining halves in half again. The whiskers represents percentiles of 5th and 95th.

Figure 2 shows that under each condition, more than 5% felt cooler than "neutral" and warmer than "warm"; more than about 50% of the subjects voted above "slightly warm", which was warmer than expected. This was ascribed to (at least partly if not all) the added thermal resistance of the padded office chair, which increased overall clothing insulation value (I_{cl}) of 0.26 *clo* over the standard 0.6 *clo* specified by Standard 55.

4.2.2 Comfort sensation

Besides thermal sensation, a 5-point comfort sensation scale (*comfortable, slightly uncomfortable, uncomfortable, very uncomfortable, intolerable*) was used to allow an evaluation of the humidity conditions in which subjects may be uncomfortable due to high humidity, skin wettedness, or any other reasons. From the ANOVA analysis (Table 3), no significant difference of the *average* vote of discomfort under the four RHs was found ($P = 0.83$).

Table 3 ANOVA for comfort sensation

	Sum of squares	Degrees of freedom	Mean square	F-ratio	*P-value*
Between RHs	0.433	3	0.144	0.300	0.83
Within RHs	38.464	80	0.481		

However, from the vote distribution (Figure 3), we can observe that the portion of subjects voting worse than "slightly uncomfortable" increased slightly with the RH level. Under the test conditions with RH ≤ 60%, more than 25% of the votes approached "slightly uncomfortable" *or worse*. When RH was ≥ 70%, more than half of the subjects became "slightly uncomfortable" *or worse*. These indicate that when RH was getting higher, more subjects were getting "slightly uncomfortable" *or worse*.

4.2.3 Skin wettedness feeling

Subjective skin wettedness feeling was measured by using a continuous scale termed *normal, damp, wet, and soaking wet*. Subjects voted their skin wettedness feeling toward whole-body, and five local body parts (forehead, armpit, abdomen, leg, and foot).

Table 4 ANOVA ($P = 0.29$) found no significant difference in subject's *average* whole-body skin wettedness feeling under the RH levels ranging from 50% to 80%. From Figure 4, we see that there were large differences in perceiving the skin wettedness perception between individuals even within the same humidity level. Similar results were found of local skin wettedness feeling votes across the RH levels from 50% to 80% by doing the same analysis on each segment, including forehead, armpit, abdomen, leg, and foot.

Table 4 ANOVA for whole-body skin wettedness feeling vote

	Sum of squares	Degrees of freedom	Mean square	F-ratio	*P-value*
Between RHs	2.484	3	0.828	1.268	0.29
Within RHs	51.595	79	0.653		

We use ANOVA to investigate whether there was difference between segment votes and the whole-body vote. No significant difference between local skin wettedness feeling was found among votes for forehead, armpit, abdomen, leg, foot, and the whole-body. Table 5 presents the results for 80% RH condition.

Table 5 ANOVA for skin wettedness feeling votes across segments under RH 80%

	Sum of squares	Degrees of freedom	Mean square	F-ratio	*P-value*
Between segments	3.359	5	0.672	1.023	0.41
Within segments	78.109	119	0.656		

Figure 5 displays the average of the whole-body skin feeling votes by each subset of subjects. The average vote increased slightly with the increase of RH level, although the changes were not significant. This also matched the result from a study by McIntyre that the perceived moistness of the skin increased slightly with humidity level up to 70% RH [23]. We also see that the *average* feeling votes from five segments was very close to the whole-body feeling vote throughout the RH ranges (Figure 5). This indicates that the whole-body skin wettedness feeling vote was a good representation for subject's overall average skin wettedness feeling.

4.2.4 Humidity perception

Past studies by Andersen et al. [24] and Rasmussen et al. [25] concluded that in high humidities up to 70% RH, humidity changes were not much perceived by subjects during 3-4 hours of exposure, and subjects exposed to constant humidity couldn't judge humidity level.

In this study, subjects voted their humidity perception on a continuous 7-point scale (*very humid, humid, slightly humid, neutral, slightly dry, dry, very dry*). No significant difference in the average humidity perception under conditions of 50%, 60%, 70% and 80% RH was found (Table 6 ANOVA with the *P-value of* 0.56).

Table 6 ANOVA for air humidity perception

	Sum of squares	Degrees of freedom	Mean square	F-ratio	*P-value*
Between RHs	2.451	3	0.817	0.631	0.56
Within RHs	103.551	80	1.294		

Figure 6 shows that in each RH condition, about 25% of the subjects voted "slightly humid" *or more humid*. Interestingly, more than 5% of the subjects perceived the air as "slightly dry" *or drier* than this, as was the case of voting "humid" *or more humid*, in each RH condition. These suggest that there was no significant difference of average person's humidity perception vote on the 7-point scale under four test conditions. In fact, some subjects reported that it was hard for them to perceive the air humidity, and even to distinguish between levels of dryness and humidity when asked the questions about air humidity perception.

4.3 Acceptability analysis

Under the recommendation of ASHRAE Standard 55-1992 [2], the combinations of indoor environmental factors and personal factors should produce thermal environmental conditions acceptable to at least 80% of the occupants. Figure 7 shows the percentage of subjects voting "acceptable" when asked for sensation acceptability in regard to thermal sensation, skin wettedness, humidity perception, air quality, etc., in four RH conditions.

In order to examine the relationship between sensation acceptability and the relative humidities, the number of subjects voting "acceptable" and "not acceptable" is tabulated for four humidity levels to apply Pearson's χ^2 test (Table 7). The *P-Value* resulting from each χ^2 test represents how significant the association between acceptability and RH level is. If the *P-Value* is smaller than the significant level as concerned (i.e. 10%), then the association is considered to be significant based on this level. In this case, the change of subjective acceptability is significant across four test conditions, thus the change of acceptability is ascribed to different RH levels.

Table 7 Pearson's χ^2 test of acceptability and humidity level

Acceptability	Pearson's χ^2	Degrees of Freedom	*P-Value*
Thermal sensation	2.088	3	0.55
Skin wettedness	6.117	3	0.11
Humidity	6.715	3	0.08
Air quality	1.875	3	0.60

From χ^2 test result, thermal acceptability ($P = 0.554$, $df = 3$) appeared to have no significant change across four *test conditions*. However, since thermal acceptability is strongly affected by temperature, and under test conditions higher RH was associated with lower temperature, the effect of humidity on thermal acceptability was evident. Thermal acceptability declined with the increase of humidities while temperature on the warm side of comfort zone decreased. This could also be found from Figure 7. These results are consistent with the finding in Berglund's study [11].

The χ^2 test for skin wettedness acceptability barely shows the significant change in skin wettedness acceptability across four RH levels based on the significant level of 10% ($P = 0.11$, $df = 3$). However, skin wettedness acceptability dropped significantly when RH was 80% (Figure 7).

With the increase of humidity, there was a significant increase in the number of subjects voting "not acceptable" for humidity perception. At the 10% significant level, humidity acceptability was significantly associated with the humidity level ($P = 0.08$, $df = 3$). With the increase of RH, the humidity perception acceptability decreased significantly.

Same analysis was done for air quality, one of the nonthermal factors (Figure 7 and Table 7). The *P-Value* of 0.6 for air quality implies no significant association between air quality acceptability and humidity.

5. Conclusions and Recommendations

- When the environment was maintained along ET^*=26.1°C with RH changing from 50% to 80%, no significant variation could be found in *average* subjective votes of thermal sensation, comfort sensation, skin wettedness and air humidity perception.
- Along ET^*=26.1°C, there was a significant increase in the number of subjects who became more uncomfortable when the humidity level was at 70% RH and 80% RH - half of subjects voted "slightly uncomfortable" *or worse*.
- The effect of humidity on thermal acceptability was evident. Higher humidity tended to contribute to the decrease of thermal acceptability.
- When RH was ≤ 70%, skin wettedness feeling was "acceptable" to a high percentage (≥90%) of subjects. When RH was 80%, there was a significant increase in the number of subjects whose skin wettedness feeling became "not acceptable". This *may* be one of the factors causing more people to get "slightly uncomfortable" under this condition.
- Humidity acceptability was significantly associated with the humidity level in that it declined significantly with the increase of RH. Humidity acceptability is not yet explicitly addressed as one of the factors affecting the definition of comfort zone in the current proposed addendum 55a to Standard 55-1992. We recommend that humidity acceptability be considered as one of the factors affecting the definition of comfort zone.
- The subjective perception of air quality acceptability appears not to be affected by humidity level significantly.
- These laboratory test results showed that the current comfort zone [2] may expand more on the upper humidity bound based on the subjective votes in regard to thermal sensation, skin wettedness feeling, humidity perception and acceptability. More tests under different set points (ET^* from 23°C to 26°C

and RH from 60% to 80% or higher) simulating the summer condotion needs to be carried out in order to achieve a more precisely defined upper humidity boundary for the comfort zone.

Acknowledgments

The authors would like to thank Hui Zhang, a research specialist at the Center for Environmental Design Research, University of California at Berkeley, Takashi Akimoto, a senior engineer from Shimizu Corporation in Tokyo, Katsuhiro Miura, a research engineer from Kajima Corporation in Tokyo, Japan, for their assistance in the project. The project was funded by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor.

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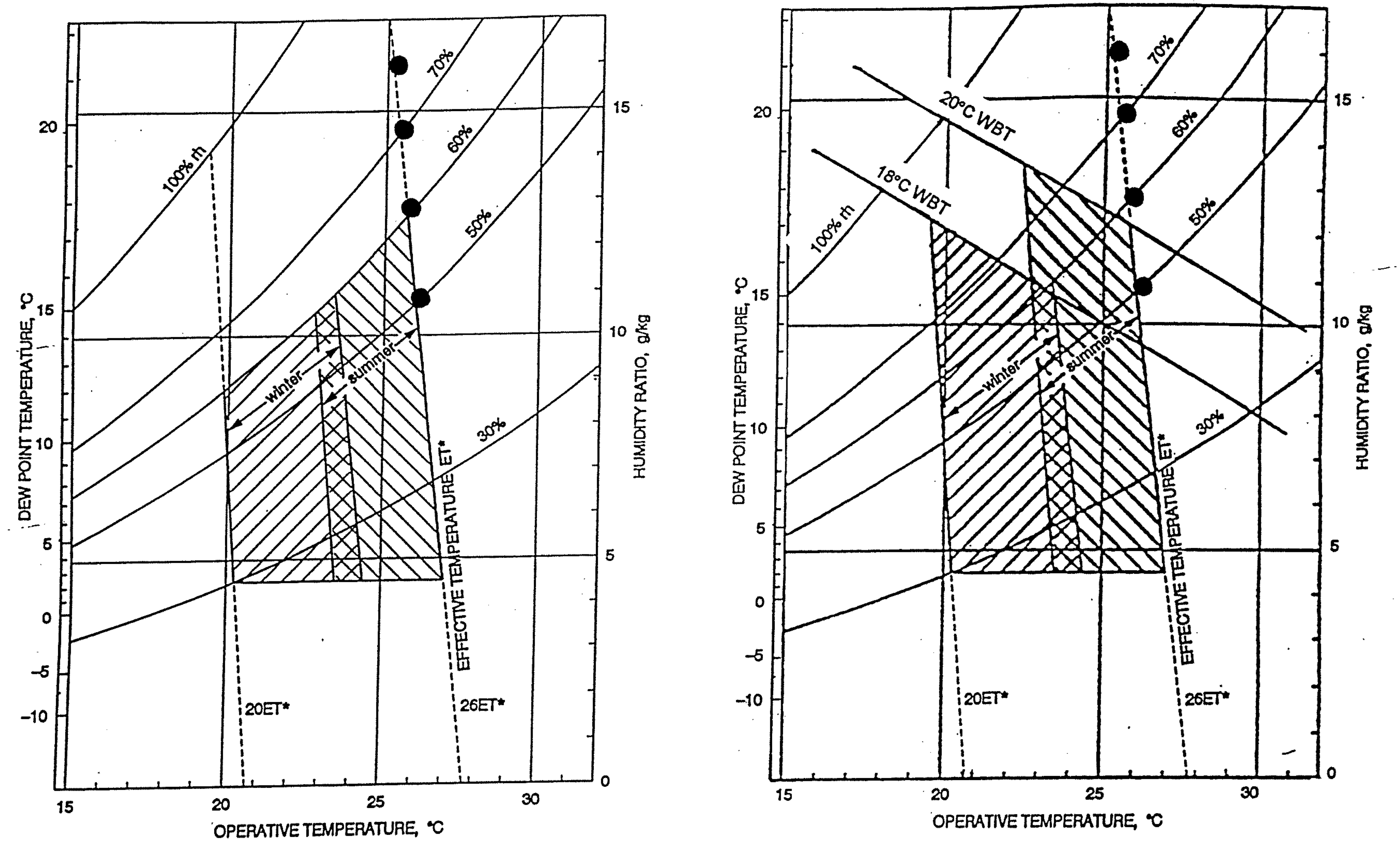

(a) Comfort Zone of ASHRAE Standard 55-92

(b) Addendum 55a to ASHRAE Standard 55-92

Figure 1. Test conditions vs. Comfort zone

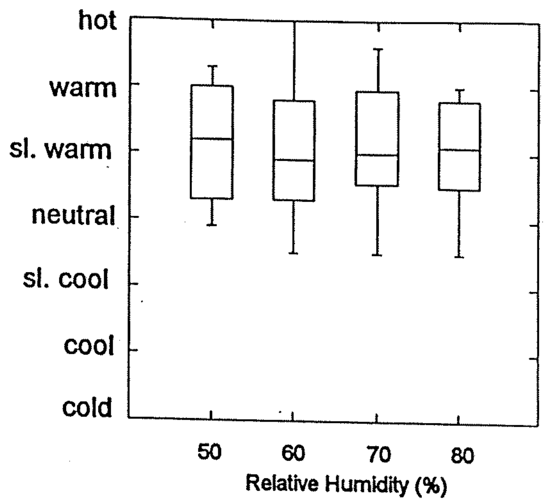

Figure 2. Thermal Sensation

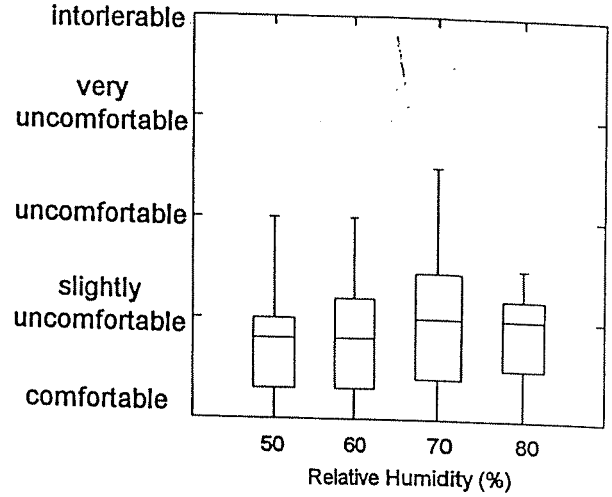

Figure 3. Comfort Sensation

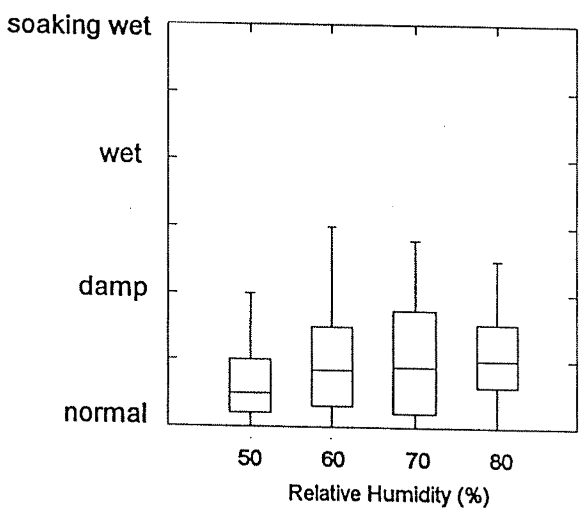

Figure 4. Skin Wettedness Feeling

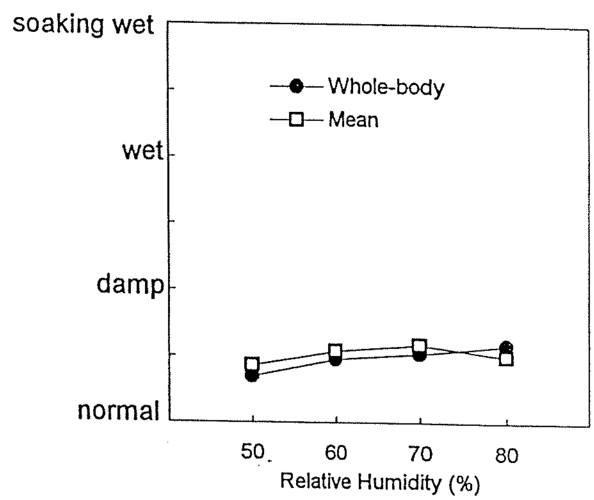

Figure 5. Skin Wettedness Comparison

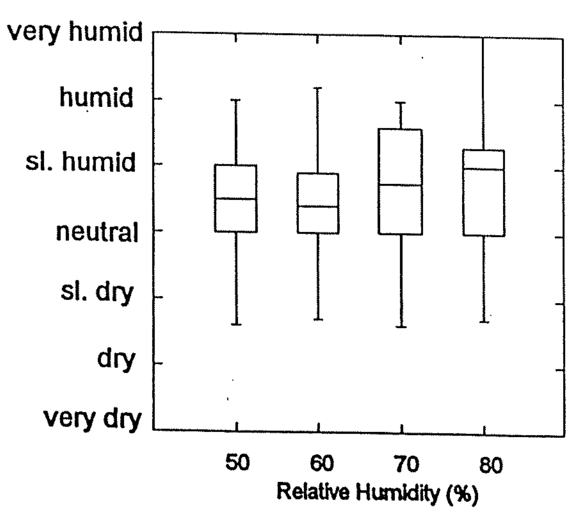

Figure 6. Air humidity Perception

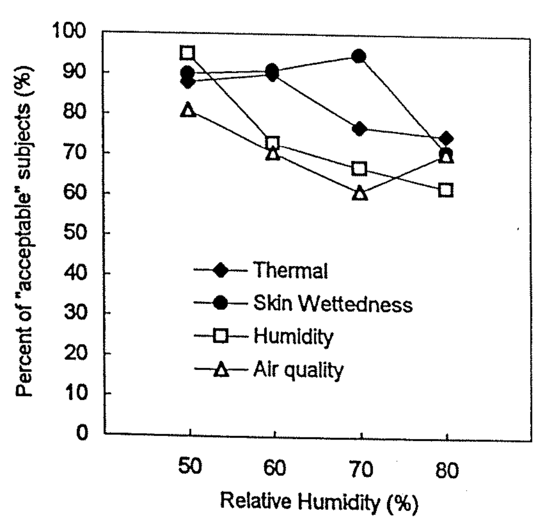

Figure 7. Subjective Acceptability