A comparison of methods for assessing thermal sensation and acceptability in the field

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Abstract

Architects, engineers, and facility managers are eager to know how to design and operate buildings to create acceptable (and perhaps even pleasurable) thermal environments. For guidance, they look to thermal comfort standards, which have been developed based on knowledge gained primarily from laboratory experiments. Laboratory studies have provided us with a wealth of knowledge in the areas of thermophysiology, heat exchange, and subjective response, and greatly contribute to the foundation of our understanding about thermal comfort.

Field studies of thermal comfort are equally important, and frequently ask different questions. For example, what thermal environments currently exist in buildings, and to what extent do they compare to people's responses in the laboratory? How do the building occupants' assessment of "acceptability" compare with what's prescribed by the standards? What do we need to know to successfully apply laboratory-based models to the field, and what additional factors occur in buildings that we either don't know enough about, or are not accounting for in the models?

In this paper, we use data from *ASHRAE 462-RP* and other field studies to examine methods for predicting thermal sensation and assessing acceptability in the field. Results show the importance of accounting for the insulation value of the chair, using new clo values given in *ASHRAE Standard 55-92* as opposed to those in *ASHRAE Standard 55-81*, and using a more realistic estimation of net value for office activity. By incorporating new values for these factors in the analysis, the laboratory based *PMV* more closely matches measured mean thermal sensation in the field.

Beyond predictions of thermal sensation, we also examine traditional methods used in standards for assessing the acceptability of the thermal environment. These include the commonly used assumption of equating specific thermal sensations with comfort and satisfaction, and the assumption that the optimum temperature corresponds to a neutral thermal sensation. Using data from several field studies, we compare people's responses to different scales to examine the validity of this approach and the potential influence of seasons. Some effects noted are that a significant number of people voting outside the 3 central categories of the thermal sensation scale find these to be comfortable; preferences for non-neutral thermal sensations are common and may change with seasons; and different measures of dissatisfaction produce widely different assessments of the acceptability of a given environment.

These issues emphasise our limited ability to answer building professionals' fundamental question about whether a building is acceptable, and raise interesting questions for future research in thermal comfort.

1 Introduction

Our ultimate objective for conditioning the interior environments of buildings is to maintain the comfort, health, and productivity of the people who occupy them. While architects, engineers, and facility managers all perform different functions in this process, they are often faced with similar questions. In designing a building and its mechanical systems, what criteria do we use to determine either the optimum or the acceptable range of environmental conditions to be produced? Or, given an existing building, how can we determine whether its interior environmental conditions are, in fact, acceptable?

For guidance in designing thermally comfortable buildings, professionals look to standards that have been generated by the research community (ASHRAE, 1992; ISO, 1984). These standards have been developed from extensive and rigorous laboratory experiments. Such laboratory studies provided a wealth of knowledge using methods from the disciplines of thermophysiology, heat exchange, and subjective response, and greatly contribute to the foundation of our understanding about thermal comfort. However, researchers are increasingly exploring the extent to which we can directly apply laboratory-based methods, without modification, to conditions in real buildings where the dynamics of both the people and the interior climate are exceedingly complex.

Field studies help to define this challenge, frequently asking questions that complement inquiries commonly used in a laboratory setting. For example, what thermal environments currently exist in buildings, and do they comply with standards? How do people respond to these environments, and to what extent do they compare to people's responses in the lab? How do the building occupants' assessment of "acceptability" compare with the intent of the standards? To what extent are people's thermal perceptions and preferences influenced by their thermal experiences and expectations? Overall, what must we know to successfully apply laboratory-based models in the field, and what additional factors occur in buildings that we either do not understand sufficiently, or are not accounting for in the models?

To address some of these questions, ASHRAE began sponsoring an ongoing series of field studies. In the first, an interdisciplinary team at the University of California, Berkeley, developed procedures for assessing thermal environments and occupant comfort in existing office buildings, and in 1987 conducted a field study of ten office buildings in the San Francisco Bay Area. A total of 2342 visits were made to 304 participants during winter and summer seasons. The project's initial objectives included developing a standard method for thermal assessment and determining whether thermal comfort standards were being met in existing office buildings. Laboratory-grade instruments, chosen to comply with the measurement specifications in the comfort standards, supplied physical data while a laptop computer-based thermal assessment survey collected subjective data from each participant. This survey included 53 fields of data addressing thermal sensation, thermal preference, comfort, mood, clothing, and activity. The specific scales that will be analyzed in this paper are shown in Figure 1. In addition, each participant completed a background survey covering demographics, health, environmental sensitivity, characteristic emotions, personal versus comparative comfort, office description, work area satisfaction, and job satisfaction. Complete descriptions of the survey method, instrumentation, and data analysis to date are available elsewhere (Schiller *et al*, 1988; Schiller 1990; Benton *et al*, 1990; Brager, 1992).

THERMAL SENSATION

Hot	+ 3
Warm	+ 2
Slightly warm	**+ 1**
Neutral	**0**
Slightly cool	**- 1**
Cool	- 2
Cold	- 3

COMFORT

Note: the term "Expanded Comfort Scale" refers to the inclusion of "slightly uncomfortable" in the definition of acceptability

Very comfortable
Moderately comfortable
Slightly comfortable
Slightly uncomfortable
Moderately uncomfortable
Very uncomfortable

PREFERENCE

I would like to be:

warmer
no change
cooler

Figure 1 Scales used in the ASHRAE San Francisco field study (shaded portions represent indirect measures of acceptability)

The process of designing the field research protocol, collecting the data, and the subsequent analysis continually generated new sets of questions about assessing thermal comfort in the field. The analysis suggested that traditional methods of investigating thermal comfort answer traditional questions very well (eg, "what is the neutral temperature of a population?"). But it also suggested that a much richer landscape exists beyond the "comfort zone." Questions about the complexities of thermal preference and acceptability often yield responses that are not easily assimilated into the established framework of thermal comfort prediction. Our comfort standards serve to prescribe acceptable conditions, yet the surveys used in the experiments on which these standards are based never asked about acceptability directly. If we are to develop a more accurate understanding of thermal comfort in real buildings, we must re-evaluate certain aspects of our conventional protocols, and perhaps develop new methods for exploring new questions.

The first part of this paper uses data from the ASHRAE San Francisco study to look at how revised estimates of clothing insulation levels (clo) and metabolic rates (met) can improve our ability to predict mean thermal sensation and neutral temperature, and acceptability. The second part of the paper uses data from five different field studies to test some of the underlying assumptions of existing thermal comfort standards, and to explore the somewhat ambiguous relationships between thermal sensation, comfort, preference, and acceptability. Our analysis will address the following questions. To what extent can we equate specific thermal sensations with acceptability? To what extent can we equate the optimum temperature with a neutral thermal sensation? Do people prefer thermal sensations other than neutral, and do these patterns change with season? What can we learn from the various indirect measures of acceptability?

2 Effect of clo and met estimations

One of the most frequently used methods for comparing measured field data to laboratory-based prediction tools is the relationship of mean thermal sensation and temperature. Earlier analysis from the San Francisco field study showed that the *PMV* index (predicted mean vote) underestimated measured mean thermal sensation by approximately ¾ of a scale unit, resulting in a difference between measured and predicted neutral temperature of approximately 2.5°C (Schiller, 1990; Brager, 1992). We attributed this discrepancy to the possibility that clothing and metabolic rate may have been underestimated in the original study. This in turn led to efforts to see how we might revise our estimates of these values, and what the subsequent effects would be on improving the match between measured and predicted thermal sensation, neutral temperatures, and acceptability in the field.

2.1 Adjusting clo value

To determine clothing levels, the thermal assessment survey used in the San Francisco study included male and female versions of a clothing checklist, presenting an itemized list of garment items and a four-point rating scale indicating the relative weight of each item. Based on the responses, we computed total intrinsic clothing insulation (clo) using procedures outlined in the *ASHRAE Handbook of Fundamentals* (1985), and *ASHRAE Standard 55* (1981). Using the most current sources at the time, we calculated an average ensemble clothing insulation of 0.55 clo, and used this value for the linear regression in our original analysis.

For the analysis in this paper, we examined two ways in which our original estimation of clo levels could be improved. First, since our original analysis, values for clothing insulation have been revised in more recent versions of the *ASHRAE Handbook of Fundamentals* (1989) and *ASHRAE Standard 55* (1992). Calculations combining these new tables with our original data increased the clo levels from our survey by an average of 0.1 units.

The second consideration was that the office chair itself could be providing additional insulation not accounted for in the tables of ensemble clo values. This was first suggested by both Dr Fanger and Dr Wyon when our original analysis comparing measured and predicted thermal sensation was first presented (Fanger, 1990; Wyon, 1990). In the laboratory experiments which form the basis for existing comfort standards, participants sat in string chairs with negligible insulation. When applying these models to a field setting, it is therefore important to account for the increased insulation provided by a more typical upholstered office chair. To estimate this effect, in 1992 Dr Shin-ichi Tanabe (Ochanomizu University, Tokyo) conducted experiments in the controlled environment chamber at the University of California, Berkeley. He used an office chair representative of those found in the field study, and a skin-temperature-controlled thermal manakin dressed in a clothing ensemble with an insulation value equal to the average clo value found in our field study. The experiment established the incremental insulation value of an office chair as approximately 0.15 clo (Tanabe, 1992).

2.2 *Adjusting metabolic rate*

The thermal assessment survey used in the San Francisco study also included an activity checklist to profile the worker's physical activity prior to taking the survey. Again using the procedures outlined in the *ASHRAE Handbook of Fundamentals* (1985), we calculated an average metabolic rate of 1.12 met, and used this value for the linear regression in our original analysis.

Source	Met
ASHRAE Standard 55 (1992)	1.2
ASHRAE HOF (1989)	1.0 - 1.4
Busch (1990)	1.1
de Dear and Auliciems (1985)	1.2
de Dear and Fountain (1994)	1.2
McIntyre (1980)	1.3
Fishman and Pimbert (1979)	1.4
Schiller *et al* (1988)	1.12

Table 1 Average metabolic rates for office work

Although we are not able to go back and collect new data on people's activity levels, we can compare our findings to other sources to get an indication of whether activity levels might have been underestimated. One source for this comparison is existing tables that correlate typical metabolic rates with different activities. For example, both *ISO Standard 7730* (1984) and *ASHRAE Standard 55* (1992) report 1.2 met for typical office work, while the *ASHRAE Handbook of Fundamentals* (1989) gives a range of 1.1 to 1.3 met for "miscellaneous office work". Another source for comparison is other field studies conducted in similar office environments. Average metabolic rates used in 5 different field studies conducted in office buildings are summarized in Table 1, covering a range of 1.1 to 1.4 met. In some cases, metabolic rate was estimated using surveys (McIntyre, 1980; de Dear and Auliciems, 1985; de Dear and Fountain, 1994), while in other cases it was estimated based on observation (Fishman and Pimbert, 1979; Busch, 1990). Looking at all these sources, an average estimate of 1.2 met might be used as a reasonable value for indoor office work, which suggests that our original analysis at 1.12 met may have slightly underestimated metabolic rate.

2.3 *Influence of clo and met estimations on PMV*

Using these estimations, Figure 2 illustrates the extent of agreement between measured and predicted thermal sensation for a series of incremental changes to clo and met based on the revisions just described. This is a plot of mean thermal sensation (measured from the survey, or as predicted by *PMV*) versus operative temperature, using the data from the San Francisco study.

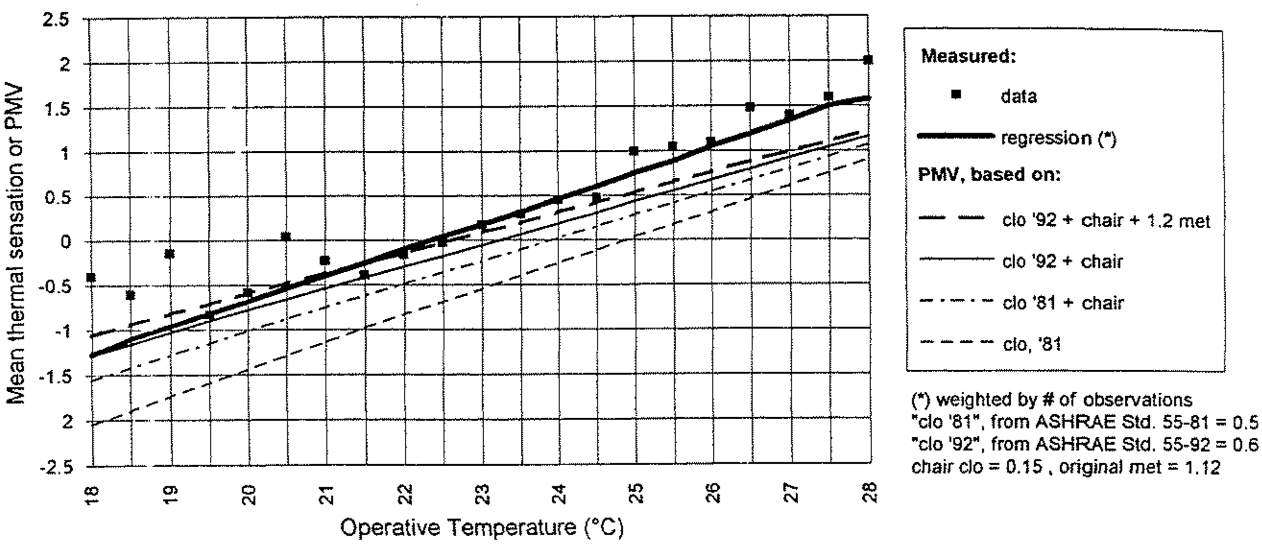

Figure 2 Influences of clo and met estimations on predicted mean thermal sensation (*PMV*)

The solid heavy line represents a linear regression of our measured data, based on a total of 2342 observations with winter and summer data combined (in our database, there was no statistically significant difference in clothing and metabolic rates between winter and summer). The linear regression is weighted by the number of observations in each operative temperature of 0.5°C. The fit is primarily determined by the data in the mid-range of 21.5-25.0°C, where the majority of our measurements occurred.

The other lines on the graph represent predicted mean thermal sensation, as calculated by *PMV*. The lowest dashed line on the graph represents our original analysis, while the remaining series of lines show the incremental effects of changing the values of clo and met. Starting from the bottom, these incremental changes are as follows:

a) original analysis, using *ASHRAE Standard 55-81* line based on clo=0.55 and met=1.12;

b) adding chair (clo=0.15) to original value, line based on clo=0.70 and met=1.12;

c) using more recent *ASHRAE Standard 55-92* (clo=0.65), plus adding chair (clo=0.15), line based on clo=0.80 and met=1.12;

d) using revised estimate of metabolic rate, line based on clo=0.80 and met=1.2.

Our original analysis showed that *PMV* underestimated mean thermal sensation by approximately ¾ of a scale unit. Although accounting for the chair certainly improves the predictions, *PMV* still continues to underestimate mean thermal sensation by 0.25 - 0.5 units. If we use the more recent 1992 sources of clo values (increasing the average clo from our survey by another 0.1 units), the match improves further, especially in the cooler temperatures.

The darkest dashed line represents our final calculation of *PMV* when both clo and met are revised. Average clo has been increased a total of 0.25 units, the combined effects of both : 1) an updated table of ensemble values, and 2) accounting for the chair. Met has been increased to 1.2 met. With these modifications, the match between measured and predicted mean thermal sensation improves considerably, especially in the regime near neutral. The difference becomes a bit wider as conditions deviate away from neutral showing that, for a given operative temperature, people are voting across more extreme thermal sensations than predicted.

2.4 Influence of clo and met estimations on predicted neutral temperature

Neutral temperature (t_n) is defined as the temperature at which the mean thermal sensation is neutral, or zero on the 7-point ASHRAE thermal sensation scale. This can be determined from Figure 2 from either the measured data or from the predictions (*PMV*). These findings are summarized in Table 2 below. Our original predictions showed a 2.5°C difference between measured and predicted neutral temperature. But when we use the most recent tables for clo values, add the chair insulation of 0.15 clo, and increase the metabolic rate to 1.2 met, the *PMV* model's predictions of neutral temperature match our measured data extremely closely, to within 0.2°C.

Estimation parameters	**t_n (°C)**
Measured neutral temperature (t_n):	22.4
Predicted t_n, based on:	
Standard 55-81, clo = 0.55 clo	24.9
Standard 55-92, clo = 0.65 clo	24.2
Standard 55-81, clo + chair = 0.70 clo	23.9
Standard 55-92, clo + chair = 0.80 clo	23.2
Standard 55-92, clo + chair + 1.2 met	22.6

Table 2 Effect of clo and met estimations on predicting neutral temperatures in the field

These results show the importance of: 1) using the most recent tables of ensemble clo values, 2) accounting for the insulation value of the chair, and 3) using a higher estimation of met value for office activity. In particular, we recommend further studies on chair insulation, and that these be included in all future revisions of standards (such experiments have recently been conducted at Kansas State University, and will be published at the ASHRAE winter Meeting in 1994). We also recommend that field study protocols include observations on the type of office chair being used, so that its insulation value can be included in the analysis. Further discussion of improved methods for estimating metabolic rate in the field would also be a welcome contribution for future field study protocols.

2.5 *Influence of clo and met estimations on PPD*

The ppd index (predicted percent dissatisfied) is based on the assumption that votes in the central 3 categories (-1, 0, +1) of the thermal sensation scale represent satisfaction, and that votes in the outer categories (±2, ±3) represent dissatisfaction (Fanger, 1972). This same assumption is used as the basis for defining acceptability, and establishing limits for the comfort zone, in current comfort standards. Using this traditional approach with the responses to the thermal sensation scale in our field survey, Figure 3 examines how more accurate estimates of clo and met can improve the match between surveyed and predicted acceptability.

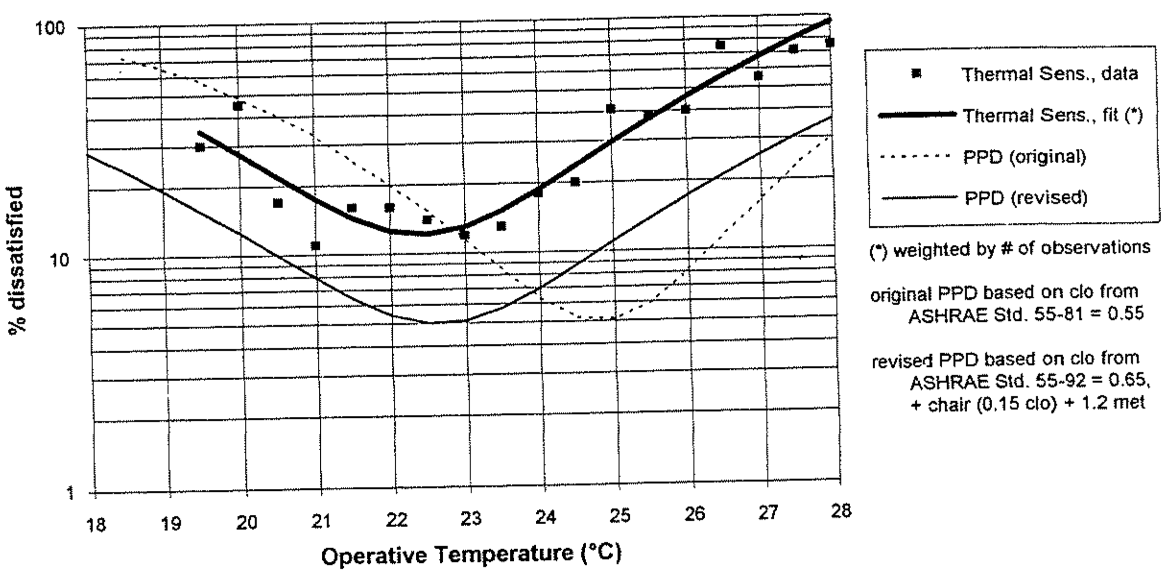

Figure 3 Influence of clo and met estimations on predicted percent dissatisfied (*PPD*)

The dots and the upper heavy solid line represent our measured data, where the fit is again weighted by the number of observations at each operative temperature. The dashed line is our original calculation of predicted percent dissatisfied (*PPD*), as published in earlier papers (Schiller, 1990; Brager, 1992). The lower solid line is our new calculation of *PPD*, based on the revised clo and met values described earlier. The higher clothing and metabolic rates result in a notable shift of the acceptability curve towards the cooler temperatures.

Optimum temperature can be defined as the temperature at which acceptability is at a minimum. As found with neutral temperature, predicted optimum temperature using the revised values of clo and met is approximately 2.3°C cooler than predictions using the original values. The two curves based on the surveyed field data and revised *PPD* are now lined up, indicating a close match between measured and predicted optimum temperature.

But while the optimum temperatures are quite close, the minimum level of dissatisfaction found in the San Francisco office buildings is still higher than predicted (or, in other words, maximum acceptability is lower). Based on responses to the thermal sensation scale, minimum dissatisfaction in the office is approximately 12%, compared to the minimum *PPD* of 5%.

Also the difference between measured and predicted dissatisfaction becomes increasingly larger as operative temperatures deviate from optimum, especially in the warm regime.

There are several possible explanations for this. One is that the *PPD* index accounts for whole body thermal sensation, while people voting in the field may be experiencing local discomfort as well and may be using the thermal sensation scale to indicate this. While this may have merit as theory, it is not a likely explanation for the San Francisco field study, since the data showed negligible air movement, vertical temperature stratification, or radiant asymmetry (Schiller *et al*, 1988).

Another factor that might account for the difference is that the *PPD* curve is calculated using a single clo value (equal to the average found in our study), while the people in the field actually wore a *range* of clothing in any given thermal environment. But the range of clo values would only partially account for this difference, implying that there are other unaccounted for factors in the field that cause people to vote over a wider range of thermal sensation, compared to the same environment experienced in the laboratory.

3 Thermal sensation, comfort, & acceptability

3.1 The meaning of these expressions

ASHRAE Standard 55 is entitled "Thermal Environmental Conditions for Human Occupancy", and it "specifies conditions in which 80% or more of the occupants will find the environment thermally acceptable" (ASHRAE, 1992). The standard then goes on to provide us with the following conceptual definitions:

> "thermal sensation: a conscious feeling commonly graded into the categories cold ... neutral ... hot";
>
> "thermal comfort: the condition of mind that expresses satisfaction with the thermal environment";
>
> "acceptable thermal environment: an environment that at least 80% of the occupants would find thermally acceptable".

"Preference" is another construct used in thermal comfort surveys, and although its definition is not specifically given in the standard, it might be defined as favouring one condition above another.

The irony here is that, while the standards use the concept of "80% acceptability" to define the comfort zone, research studies in both the laboratory and field have rarely asked individuals the seemingly straightforward question "are these conditions acceptable?" Instead, we commonly ask about "thermal sensation", occasionally we ask about "thermal comfort", and in a few instances we ask about "preference". And then we often assume a correspondence between these variables and the notion of acceptability. In reality, each of these expressions are qualitatively very different. And while technology provides us with increasing accuracy in our physical instrumentation, and our overall research protocols become more rigorous, in the final analysis we are still relying on fairly tenuous logical links to get to our final conclusions.

Of all these terms, "acceptability" perhaps has the broadest meaning. In a general sense, it might be interpreted as what the occupant is agreeable to, or approves of. This is particularly relevant for buildings with centralized controls, where each person can't individually create their own ideal conditions and the design and operating procedures try to satisfy the greatest number of people with a standard interior environment. "Preference", on the other hand, represents the ideal, referring to the conditions you would favour if you could have exactly what you wanted at any given moment. In comparison, this would perhaps be more relevant for designing task conditioning systems. And while "thermal sensation" is strongly influenced by physiological phenomenon, and "thermal comfort" is perhaps more subjective and elusive, there has been sufficient evidence in the literature to suggest that both are affected by the less understood issues of adaptation and expectation.

3.2 Scales used as indirect measures of acceptability

Laboratory and field studies have used a combination of scales in their surveys. The most common, shown in Figure 1 as used in the San Francisco study, are the 7-point ASHRAE thermal sensation scale, a comfort scale (slightly different versions have been used), and the preference scale. In the absence of directly asking a survey participant if he or she finds the conditions acceptable, each of these other scales are used instead as an indirect measure of acceptability, simply by assuming that certain votes imply that the person finds the environment "acceptable". Examples of this association are indicated by the boxed and shaded portions of the scales.

The most commonly used method for assessing acceptability is to assume a relationship between thermal sensation and satisfaction. This indirect measure equates the three central categories of the thermal sensation scale with satisfaction (or acceptability), and is the basis for the *PPD* index (Fanger, 1972) and the comfort zones of both the ISO (1984) and ASHRAE (1992) comfort standards.

Associating acceptability with votes on the comfort scale is not immediately straightforward. Some researchers use gradations of the comfort scale that include the choice "slightly uncomfortable". Since "slightly cool or warm" on the thermal sensation scale is considered to be acceptable, what then can we say about "slightly uncomfortable"? For the sake of analysis in this paper, we will look at this scale to define acceptability in two different ways. Referring to Figure 1, the phrase "comfort" will imply only the shaded region ("slightly comfortable" or better), while the phrase "expanded comfort" implies the fully boxed region ("slightly uncomfortable" or better).

Although not commonly done, the preference scale can also be used as an indirect measure of acceptability. For this purpose, and using the 3-point form of the scale shown in Figure 1, we will associate acceptability with a vote of preferring "no change".

4 A comparison of the scales as applied in field studies

4.1 *Assessing whether an environment is thermally acceptable*

ASHRAE Standard 55 defines an acceptable thermal environment as "an environment that at least 80% of the occupants would find thermally acceptable" (ASHRAE, 1992). How does one determine whether that criteria is being met? Examples of the methods one might use are as follows:

1) survey the occupants, asking "do you find this environment thermally acceptable?", and determine whether a minimum of 80% answer "yes";

2) compare the extent to which the interior environment meets the physical specifications of the *ASHRAE Standard 55* comfort zone (in this method, one is accepting the premise that, if the interior climate does fall within the limits of the comfort zone, then a minimum of 80% of the occupants will find these conditions acceptable);

3) using the same assumption on which the comfort zone is based, survey the occupants using the thermal sensation scale, and determine whether a minimum of 80% of the votes are within the 3 central categories;

4) using other scales as alternative indirect measures, again survey the occupants and determine whether a minimum of 80% of the votes on each scale fall into their respective definitions of acceptability.

The first option is truly the only direct measure of acceptability, but this question has been asked only rarely in either laboratory or field studies (and none of the studies analyzed in this paper asked about acceptability directly). The second option, analysing the physical characteristics of the interior climate, was done previously for the San Francisco study (Schiller *et al*, 1988). But a similar comparison across the five field studies is beyond the scope of this paper.

Instead, this paper uses data from the field studies as a vehicle for examining the relative performance of the different scales that might be used as indirect measures of acceptability. Later sections of the paper analyze people's simultaneous responses to the scales, and also looks at responses as a function of operative temperature. Table 3 begins with a simple summary of the data from these five field studies using methods 3 and 4 listed above.

All of these field studies used the traditional thermal sensation scale, while responses to the comfort and preference scales can each be compared only for a subset of the five studies. Simultaneous responses to these scales will be analyzed in more detail in the sections to follow. But this table begins to suggest that these scales, as alternative indirect measures of acceptability, all provide very different answers to the question "is this environment acceptable".

Field study	Indirect measures of acceptability			
	Thermal sensation	**Thermal comfort**	**Expanded comfort**	**Thermal preference**
Schiller *et al* (summer)	84%	71%	91%	52%
Schiller *et al* (winter)	82%	73%	92%	53%
Gagge (summer)	61%	68%	-	-
Gagge (winter)	62%	79%	-	-
Howell and Kennedy	72%	58%	90%	-
McIntyre (summer)	74%	-	-	49%
McIntyre (winter)	66%	-	-	49%
Busch	80%	-	-	42%

Definitions of acceptability, using indirect measures:
Thermal sensation: votes within the 3 central categories, "slightly warm/cool or neutral"
Thermal comfort: votes of "slightly comfortable" or better
Expanded comfort: votes of "slightly uncomfortable" or better
Thermal preference: votes of "preferring no change"

Table 3 Thermal acceptability - percentage of occupants finding the environment thermally acceptable, as derived by different scales

4.2 Is "neutral" always ideal?

ASHRAE Standard 55 is based on the assumption that people prefer a "neutral" thermal sensation (a vote of zero on the 7-point ASHRAE thermal sensation scale), and that discomfort varies symmetrically as sensations differ from neutral on either the warm or cool side. We can examine the validity of this assumption by looking at people's simultaneous responses to both the thermal sensation and preference scales, and determine the extent to which a neutral thermal sensation is preferred by people in the field.

Figure 4 is a histogram of data from 3 field studies which used both the thermal sensation and preference scales in their surveys. Two of the field studies (Schiller *et al*, 1988; McIntyre, 1978) published separate data for winter and summer seasons. Data from the 3rd study (Busch, 1990) showed negligible seasonal differences and was published for the combined seasons. Each bar is based on the group of people voting zero (neutral) on the thermal sensation scale, and represents the percentage (%) of that group that would simultaneously prefer to feel warmer or cooler.

Busch's study from Thailand stands out as showing that over ⅓ of the people experiencing a neutral thermal sensation still preferred to feel cooler. This begins to suggest that people's thermal sensation in the field may be influenced by culture and climate, and associated issues of thermal expectations and adaptation. McIntyre's study was particularly interesting in that it showed a clear seasonal difference in people's preferences. His data shows that in the hot summer of New Haven, Connecticut, more people preferred a cooler thermal sensation, compared to a cold British winter where more people preferred a warmer sensation. Although our own study in San Francisco did not show this seasonal difference, this was not surprising due to the annual stability of our climate.

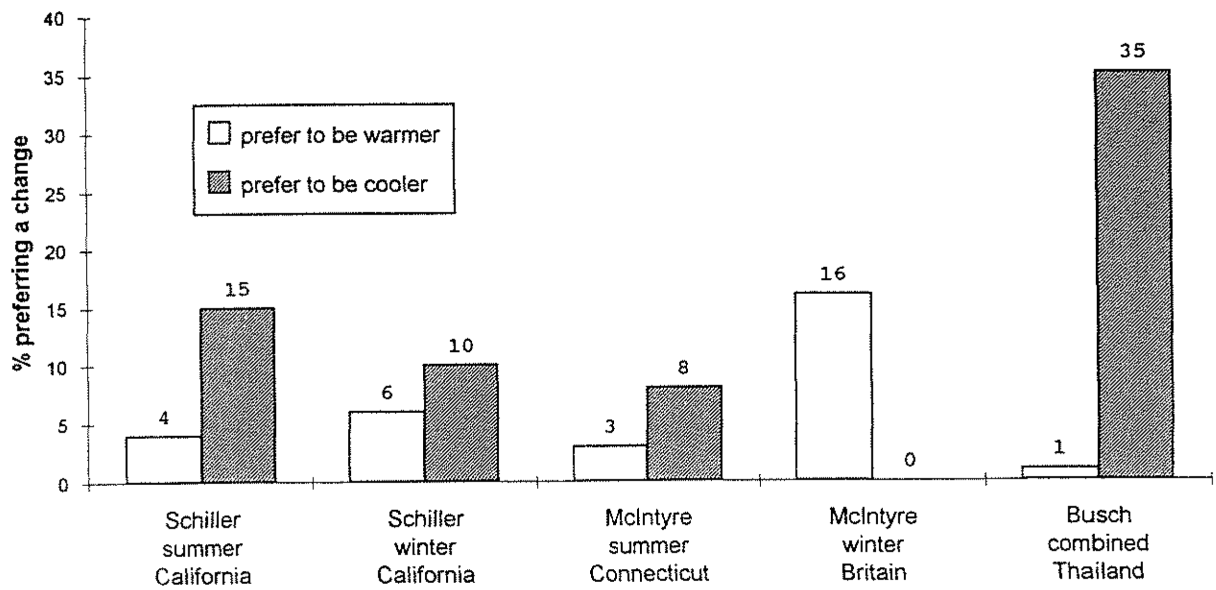

Figure 4 Preferred non-neutral thermal sensations: % of people voting neutral thermal sensation who would prefer to be warmer or cooler

With the exception of McIntyre's winter study, the majority of people in these studies who preferred non-neutral thermal sensations favoured cooler sensations more often than warmer ones. Overall, this data shows that while the majority of people experiencing a neutral thermal sensation would prefer to feel that way, there still remains a substantial proportion of the people who prefer a non-neutral thermal sensation. This has implications for the way we define optimum conditions for buildings, and whether to provide task conditioning systems (and how to design them) to allow individuals to create those preferred conditions.

4.3 *What thermal sensations are acceptable?*

The previous graph showed whether people who were already experiencing a neutral thermal sensation would prefer to feel warmer or cooler. The next 2 graphs examine people's votes across the full range of the thermal sensation scale to determine the extent to which different degrees of thermal sensation are felt to be acceptable. For this analysis, acceptability will be defined in two different ways, by people's simultaneous votes on either: 1) the preference scale or 2) the comfort scale. This analysis looks not only at how the validity of the neutrality assumption may change with seasons, but more specifically examines the traditional method of assuming that the outer categories of the thermal sensation scale represent discomfort and dissatisfaction.

4.3.1 Using the preference scale

Figure 5 compares acceptability and thermal sensation by defining acceptability as a vote of "no change" on the preference scale.

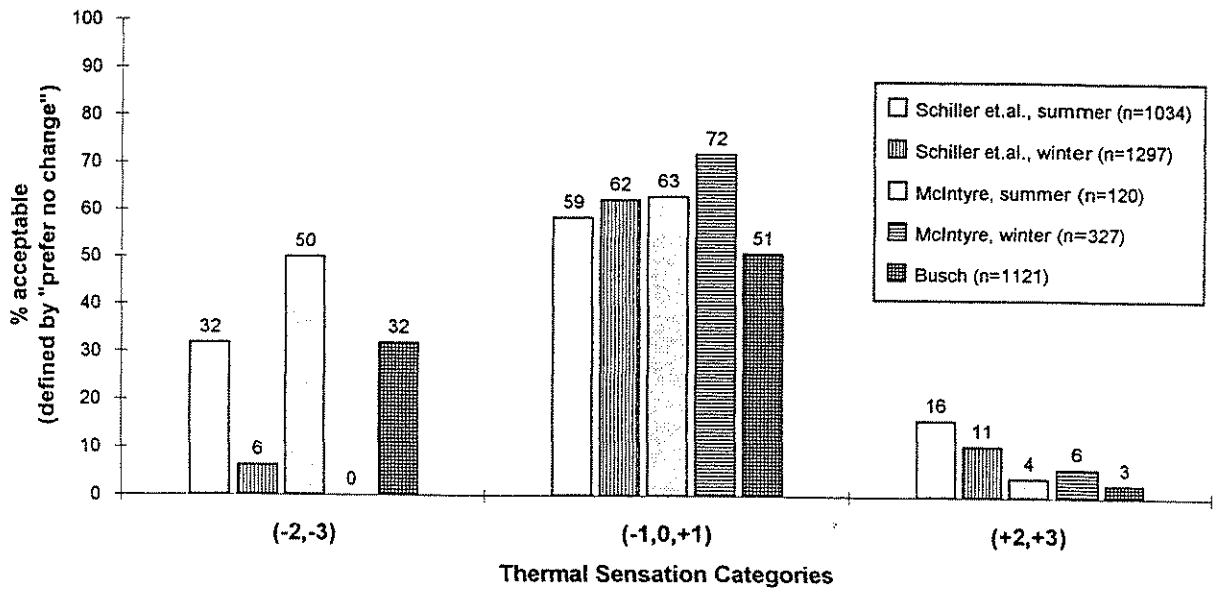

Figure 5 Preference versus thermal sensation scales: a comparison of different studies and seasonal differences

The 5 bars represent the same 3 studies as in Figure 4, two of which are again separated into 2 seasons. The x-axis represents the thermal sensation scale divided into 3 groups: the central 3 categories, and the 2 extremes of (-2, -3) and (+2, +3). Each bar is based on the group of people voting in that thermal sensation category. The height of the bar, the y-axis, represents the percentage (%) of people in each of those groups who found the conditions acceptable, in this case defined by the preference scale.

Looking first at the group of people voting within the 3 central categories of the thermal sensation scale, between ½ and ¾ of this group (51-72%) preferred no change in their conditions, with the other ¼-½ (28-49%) preferring a different thermal sensation. Looking next at votes in the extreme thermal sensations, in general more people found the cool sensations to be comfortable compared to the number favouring the warm sensations. Looking at seasonal differences, data in the cool sensations (-2, -3) show a fairly predictable pattern in that cool sensations were found to be comfortable significantly more frequently in the summer as compared to the winter. For the studies that published data separately for the 2 seasons, 32-50% of the people voting (-2, -3) simultaneously said they preferred no change, implying that these sensations did not necessarily represent discomfort. Seasonal patterns are not as consistent for the warm sensations.

4.3.2 Using the comfort scale

Figure 6 is similar to the last graph, but now compares acceptability and thermal sensation by defining acceptability as votes of "slightly comfortable" or better on the comfort scale.

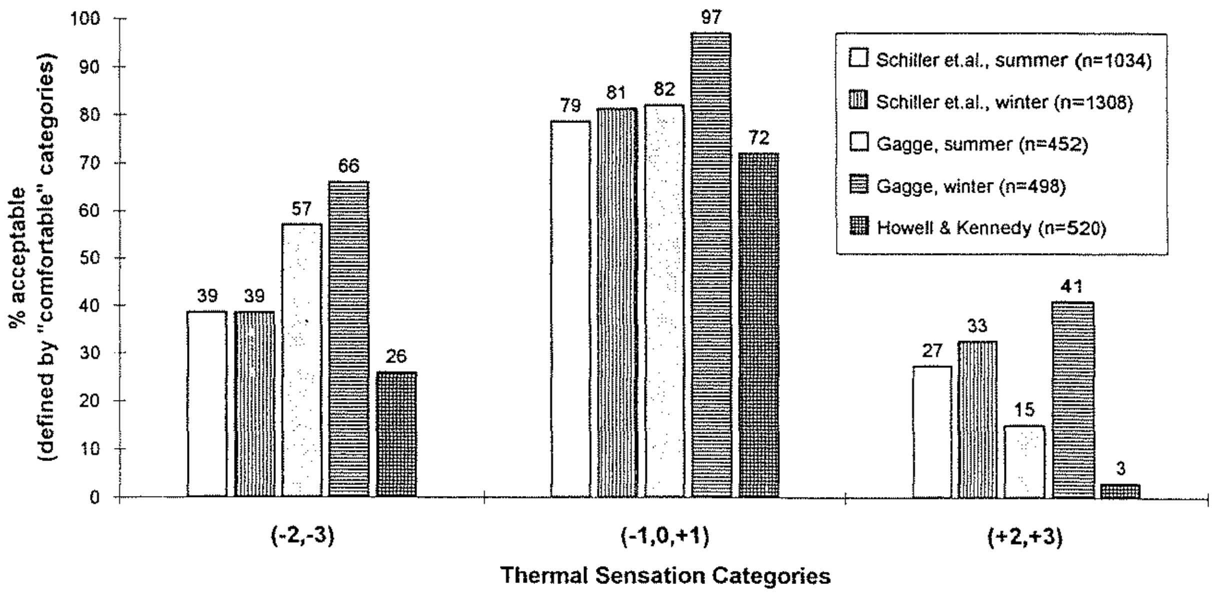

Figure 6 Comfort versus thermal sensation scales: a comparison of different studies and seasonal differences

Looking first at the group of people voting within the 3 central categories, this graph can be compared with the previous one. The data shows that defining acceptability using the comfort scale results in a higher correlation with the central thermal sensation categories, compared to associating acceptability with responses to the preference scale. Based on responses to the comfort scale, there was a much higher rate of satisfaction, with 72-97% finding conditions acceptable, and an overall average of 81% from all of the studies combined.

In a general sense, the data is consistent with the last graph in showing that the extreme cool sensations were consistently found to be more comfortable than warm sensations. Looking at the mean of all 5 data sets, and again using the comfort scale as the indirect measure of acceptability, 43% of all the people voting cool sensations simultaneously found these acceptable, while 26% of the people voting warm sensations found these acceptable.

The comfort scale does not reveal conclusive seasonal differences. Gagge's study of a New York office building showed that people found both the warm and cool extreme thermal sensations more comfortable in the winter than they did in the summer. But the strongest seasonal difference for this study is seen in the warm regime, where these sensations were frequently more comfortable in the winter than the summer. This pattern was also found in the San Francisco study, although to a lesser degree (as might be expected due to its temperate climate).

4.4 *How "comfortable" is "acceptable"?*

Most research studies use a version of the comfort scale that includes different gradations of both "comfortable" and "uncomfortable", as shown in Figure 1. Our traditional method of associating acceptability with thermal sensation prescribes that "slightly" warm or cool is still acceptable. How, then, can we apply this same logic to the comfort scale? Since both are indirect measures of acceptability, where then do we draw the line on the comfort scale? If our standards attempt to prescribe the limits of an "acceptable environment" that minimizes but admittedly can't avoid all complaints, then how "comfortable" *is* acceptable? Is "slightly uncomfortable" still acceptable?

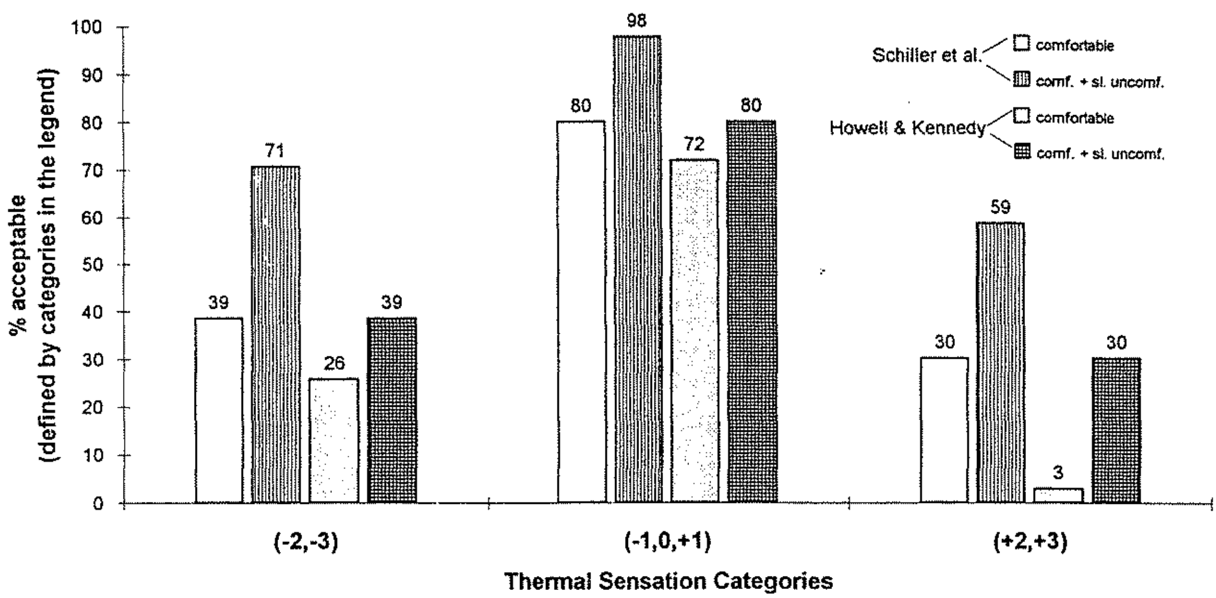

Figure 7 Gradations of the comfort scale: which scale categories constitute "acceptability"

Although we can't provide a precise answer here, we can begin to explore this question by looking at acceptability as defined by these two dividing lines on the comfort scale ("slightly comfortable" and better, or "slightly uncomfortable" and better). This is shown in Figure 7, for the 2 studies that used versions of a comfort scale that included the category "slightly uncomfortable". As with the previous graphs, these responses are again compared to simultaneous responses on the thermal sensation scale. The convention to the histograms is the same, where each bar is based on the group of people voting in the noted thermal sensation category, and the height of the bar represents the percentage of people in each of those groups who found the environment acceptable, as defined in these two different ways.

If we define acceptability in the narrower term, (excluding "slightly uncomfortable"), less than 80% in these two studies of the people find the central 3 thermal sensation categories to be acceptable. But when we expand the definition of acceptability to include "slightly uncomfortable", this increases to 80-98%.

It is also useful to look at the trend in the more extreme thermal sensations. As we again expand the definition of acceptability to include "slightly uncomfortable", we find an even greater rise in the number of people finding the more extreme thermal sensations to be acceptable as well. For the San Francisco study in particular, 59-71% of the people found the extreme thermal sensation categories to be no worse then "slightly uncomfortable".

These histograms collectively allowed us to test the validity of several traditionally accepted assumptions: 1) neutrality represents ideal conditions; 2) discomfort varies symmetrically around neutral, and 3) acceptability can universally be associated with specific thermal sensations. While these assumptions originated from laboratory experiments, this analysis shows that they are not necessarily supported by field data. The data presented here demonstrates that: 1) neutrality is not, in fact, necessarily ideal for a significant number of people; 2) people's preferences for warm versus cool sensations vary asymmetrically and, in several cases, are also influenced by season; and 3) thermal sensations outside of the 3 central categories do not necessarily reflect discomfort for a substantial proportion of people voting in the field. This leads us to question whether these assumptions represent weak links in our ability to predict or assess the acceptability of the thermal environment.

5 Acceptability as a function of temperature

The last graph (Figure 8) uses the data from the San Francisco study to compare the alternative indirect measures of acceptability as a function of operative temperature, and the resulting ranges of acceptable temperature limits that might establish a comfort zone for the buildings studied.

The lower solid line is the *PPD* curve using the revised clothing and metabolic rates. The other lines are all based on results from the field survey, where each of the indicated scales is used as an indirect measure of acceptability. For each scale, acceptability is defined in the same ways that have been described for the previous graphs. The curves represent fits to the data, weighted by the number of observations at each operative temperature bin.

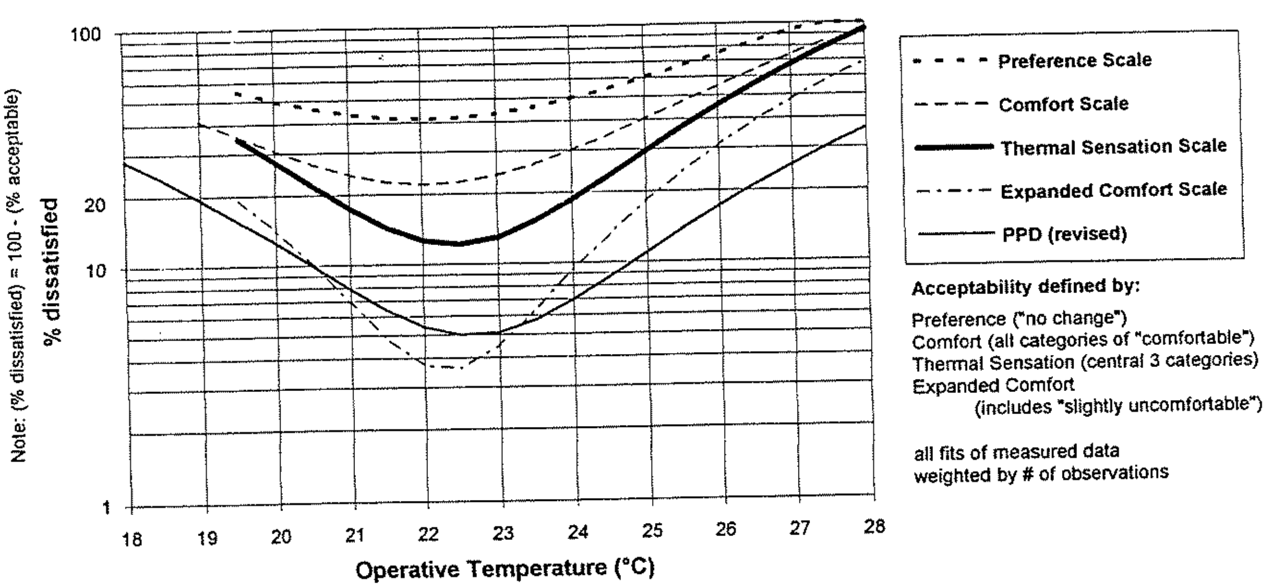

Figure 8 Indirect measures of acceptability

The highest levels of acceptability are achieved by a definition based on the expanded comfort scale, while the lowest levels are based on preference. These curves suggest that the preference scale, in its current form, is perhaps an unrealistic measure of acceptability. This may be due to semantics where a stated preference for a more ideal set of conditions, if given a choice, might not necessarily imply that the existing conditions are unacceptable. The difference in results may also be attributed to using a 3-point scale for preference, where "acceptability" is being defined strictly in terms of votes in the one category. If the preference scale was instead presented with finer gradations (ie prefer to be: slightly warmer, warmer, much warmer), perhaps the results would be more comparable to the performance of the other scales. Nonetheless, the preference scale is still useful for giving us information about what people actually want, and may be particularly important in the design of task conditioning systems where each worker would, in fact, be able to obtain their preferred thermal experience.

Another question that remains is, if using the comfort scale, which categories are best associated with acceptability? If we use categories of "slightly comfortable" or better, less than 80% find the conditions acceptable even in the best conditions. If we include "slightly uncomfortable" feelings as within the acceptable range, then we find a maximum of over 96% acceptability.

This graph illustrates that these alternative indirect measures all produce widely different assessments of acceptability of any given thermal environment, and emphasizes the need for future field studies to include the relatively straightforward question "do you find this environment thermally acceptable?".

Method used to define "acceptability"	**Operative temperature range for different levels of acceptability:** ≥80% (20 *PD*)	≥90% (10 *PD*)
Measured scales:		
Thermal sensation scale (acceptable = -1, +1)	20.9 - 24.1°C	
Expanded comfort scale (acceptable = "comfortable" + "slightly uncomfortable")	19.4 - 25.2°C	20.5 - 24.1°C
Predicted percent dissatisfied (*PPD*):		
Based on original clo and met	22.0 - 27.3°C	23.3 - 26.3°C
Based on revised estimations of clo and met	18.9 - 26.4°C	21.0 - 24.8°C

PD = percentage dissatisfied

Table 4 Temperature limits for 80% and 90% acceptability

5.1 Acceptable temperature limits

Drawing lines on Figure 8 at 10% and 20% dissatisfied (90% and 80% acceptability, respectively) allows us to determine the range of acceptable temperature limits based on the indirect measures of acceptability from the field survey, and well as the indirect predicted levels of acceptability using the *PPD* index. (Figure 3 also showed *PPD* using both the original and revised clo and met levels). As summarized in Table 4, the resulting "comfort zones" can vary substantially.

Table 4 clearly suggests that our ability to assess acceptability through surveys can produce widely different results, depending on how we actually define "acceptability". It also reveals that our ability to predict acceptable temperature limits using *PPD* is strongly influenced by our ability to estimate clothing and metabolic rates that are typical for the office space (and these estimations clearly remain an inexact science).

6 Conclusions

Laboratory-based thermal comfort standards and predictive models are commonly used to determine acceptable operating conditions for maintaining indoor environments, or to assess the acceptability of an existing environment. These standards and models require estimates of mean clothing and metabolic rates for the people and the buildings, and are also based on several simplifying assumptions about thermal acceptability of the indoor environment. This paper used data from five different field studies to examine methods for predicting thermal sensation and assessing acceptability in the field.

The first part of the paper looked at how revised estimates of clothing insulation levels can improve our ability to predict mean thermal sensation and neutral temperature, and acceptability. Results show the importance of: 1) using the most recent tables of ensemble clo values, 2) accounting for the insulation value of the chair, and 3) using a higher estimation of met value for office activity. In particular, we recommend: 1) further studies on chair insulation, 2) that all future revisions of the thermal comfort standards include tables of chair insulation values, 3) field study protocols include observations on the type of office chair being used, so that its insulation value can be included in the analysis, and 4) further discussion of improved methods for estimating metabolic rate in the field.

The second part of this paper tested some of the underlying assumptions of existing thermal comfort standards, and explored the somewhat ambiguous relationships between thermal sensation, comfort, preference, and acceptability. Examples of assumptions tested include: 1) a neutral thermal sensation represents ideal conditions; 2) discomfort varies symmetrically around neutral sensation, and 3) satisfaction, or acceptability, is associated with thermal sensation votes within the 3 central categories of the 7-point ASHRAE thermal sensation scale. Our data shows that: 1) neutrality is not, in fact, necessarily ideal for a significant number of people; 2) people's preferences for non-neutral (warm or cool) thermal sensations are common, vary asymmetrically around neutrality, and in several cases are influenced by season; and 3) thermal sensations outside of the 3 central categories do not necessarily reflect discomfort for a substantial proportion of people voting in the field. Different indirect measures of dissatisfaction produce widely different assessments of the acceptability of a given environment, leading us to question the extent to which these assumptions represent weak links in our ability to predict or assess the acceptability of the thermal environment.

These findings emphasize our limited ability to answer building professionals' fundamental questions about whether a building is acceptable. The important relationship between thermal sensation, comfort and acceptability remains poorly understood, and future work needs to draw stronger connections between laboratory and field methods, while utilizing more direct assessments of comfort and acceptability .

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Open discussion

David Won: The semantics of the ASHRAE thermal sensation scale have never appealed to me. I have always avoided using them because I think they are appropriate for a psychometric study but not for drawing conclusions about the heating and ventilation of buildings. Thomas Bedford got it right long before the ASHRAE scale was introduced. His seven-point scale defines -2 and -3 as 'too cold' unequivocally, and +2, +3 as 'too hot', and the decision as to whether they are acceptable is left to the subject. You do not have to argue about the semantics after they have told you it is too hot. It is either too hot or not too hot and it is either too cold or not too cold. The advantages of Bedford's seven-point scale are that it gives a linear relationship with temperature just as ASHRAE does, and it is useful for smoothing data, and it also gives you unequivocally the information that it is not too hot or not too cold. So I recommend for future research that the ASHRAE scale should fall into well deserved disuse, and that Bedford's thermal scale should be used instead.

Gail Brager: I agree with many of your points but think that we need to go one step further. We are still talking about comfort, which is important, but all of the standards are talking about 'acceptable' conditions. They use the word 'acceptable environment' meaning that it may be uncomfortable, but 'hey okay I can deal with it'. So maybe we need to have a

Bedford type scale which uses 'acceptably slightly warm'. We need something that brings in a direct determination of acceptability.

David Won: I do not agree. Too cold is too cold and too hot is too hot. It is not acceptable to be too cold or too hot, the decision has been made by the subject.

Richard De Dear: In my experience in field studies it seems to make no difference whether the ASHRAE scale or the Bedford scale is used. The responses of the subjects are virtually identical on these two scales.

Gail Brager: That is why I think that even if the Bedford scale is better it will not completely answer our need for a direct measure of acceptability.

Ole Fanger: Don McIntyre did a large comparison between the scales in laboratory studies, and as far as I remember there was very little difference between these two scales.

Michael Humphreys: Some years ago I compared the behaviour of scales in field studies. The conclusion was that their behaviour depended more on the number of categories than on the detailed labels. If you had a three category scale: 'too cool' to 'comfortable' to 'too warm', the centre category width was the same as for the Bedford scale. What is reported as 'too cool' using a three category scale corresponds to 'comfortably cool' using a Bedford seven-point scale, so I do not agree with David Won on this point.

Jouni Jaakkola: One essential difference in going from the laboratory to the real environment is the implication of the new time reference period. For the longer period of time you get into the question of how frequent is the condition, rather than just 'how do you feel at this point in time?'. That then leads on to the question of the environment as a function in time. So I am questioning the direct benefit of using the same scale in the laboratory as in the field. I think we have to ask different questions when we get into different environments.

Gail Brager: I think there needs to be a core group of questions that are asked in both environments. One of the things we have begun to do in field studies is to ask people about ways in which they modify their behaviour or their environment. We note if they have windows which they can open, blinds that can be drawn, or fans that can be operated. We note at each work-station what controls they have available to them, and the computer is coded so that those questions come up. We ask them whether they use such controls, and for those that do, a second question asks how effective they are. So I think there are a series of questions in addition to, not instead of, those used in laboratory studies.

Nigel Oseland: In my own field studies, and in those of other researchers, I found that people preferred in winter to feel slightly warm and in summer slightly cool. So do we need to make an adjustment to account for the preferred points on the thermal sensation scales? I found that I get more agreement if I take the temperature for the 'slightly warm' sensation in the field and relate it to the 'neutral' temperature found in the laboratory situation. Does this mean that we should use different scales in the field and in the laboratory? Can we get away with a thermal sensation scale or do we need one that relates more to a person's context?

Gail Brager: I think that is the direction we need to go. As we refine our ability to understand, predict and design for acceptable thermal environments, we have to take the context into account. Whether we can predict what the context of an office versus a home environment will be, or of a British winter versus a New Haven summer, I do not know. We need more work in that area but my personal belief is that we are beginning to understand context. We need to ask questions in different ways. The field studies can eventually add to our understanding. Also the laboratory studies can be constantly improved and refined to increase our ability to answer those questions.