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The Correlation Between PMV and Dissatisfaction on the Basis of the ASHRAE and the McIntyre Scale – Towards an Improved Concept of Dissatisfaction

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Key Words

Thermal dissatisfaction · PPD · PMV · McIntyre · Preference · Gender · Age · Building type · Outdoor temperature · Indoor conditions

Abstract

This paper proposes a concept of dissatisfaction that is based on the correlation between the McIntyre and the ASHRAE votes of the ASHRAE RP-884 Adaptive Model Project – Data. The correlation shows that people who are voting with ASHRAE ±2 or beyond are not necessarily dissatisfied (which is the basic assumption of the classical PPD concept) and vice versa, that people who are voting between −1 and 1 are not necessarily satisfied with their thermal environment. The data set was divided into several factors (age, gender, building type, indoor conditions, outdoor temperatures) to analyze any dependencies of the preference on these factors. Processing the data finally lead to a predictive system that is – applied to the source data – a better predictor for preference than the PPD. This improvement needs affirmation by the application of the predictive system to an independent data set.

Nomenclature

mASHvote – mean ASHRAE vote
mPREFvote – mean Preference vote
PMV – Predicted Mean Vote
PPD – Predicted Percentage Dissatisfied
PPD* – improved PPD concept
PPMV – Predicted Preference Mean Vote
corr – corrected

Introduction

This paper is based on the assumption that people who prefer no change of their thermal environment are satisfied and people who prefer a change of their thermal environment – be it warmer or cooler – are not satisfied with

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their conditions. This looks trivial at first sight, but it is not. As a matter of fact it accepts that on the one hand, people are not always satisfied when voting with a neutral ASHRAE vote but on the other hand might be satisfied when voting for a ASHRAE score (different from −1/0/1).

This contradicts the PPD concept of Fanger [1] which statically assumes, that people who are voting with −2/2 or beyond are dissatisfied. This assumption is based on findings of Gagge [2] who found a nonlinear relation between the ASHRAE scale and grades of discomfort. This nonlinearity leads to votes of −1/1 (slightly cool, slightly warm) being relatively close to comfort, graphically represented by a right-shift of the correlation between ASHRAE votes on the x-coordinate and discomfort on the y-coordinate.

The classical PPD equation is based on the distribution of thermal sensation votes found in Fanger's experiments. As the PMV is supposed to be a mean vote of a larger group of people it includes votes different from the numerical value of the PMV. The distribution of votes is wide enough to include votes of −2/2 and beyond even for a PMV of 0. This leads to a minimum of the PPD curve different from zero, i.e., 5%, and an increasing number of dissatisfied people with PMVs different from 0.

The idea for a modified PPD concept (PPD*) is to cross tabulate ASHRAE votes and Thermal Preference votes of a large data base in order to calculate the fraction of people who are dissatisfied, warm or cold, for each ASHRAE vote category (ranging from −3/3). As the distribution of ASHRAE votes for a PMV is known from Fanger's experiments the total number of dissatisfied persons can then be calculated based on a single PMV value. This is done by calculating the percentage of dissatisfied people for each ASHRAE vote category and then adding the results weighted with the share the ASHRAE vote has in the PMV.

Based on a calculated PMV value the PPD* should be a better predictor of the individual preference (''prefer warmer'', ''prefer cooler'') than the classical PPD. This however requires a good predictive quality of the PMV for ASHRAE votes (compare Humphreys [3]). Based on the ASHRAE vote of an individual, the PPD* should also be a better predictor of the preference than are the Gagge findings.

The correlation between ASHRAE vote and Preference vote is not static. In fact, it depends on the one hand on characteristics of the individual and on the other hand on characteristics of the situation the person is in. Therefore the dependencies of this correlation on a number of important factors that can be objectively described (such as age, gender and so on; see below) were analyzed. However, there are certainly more influencing factors than those analyzed and in combination with individual characteristics these set limits for the predictive quality.

It is also necessary to mention, that this paper is a conceptual paper. It proposes a theoretical method to develop a better predictor for potential user behavior in a building which is part of a more sophisticated psychological model that will be presented soon (paper in preparation). The quantitative results might not be free from data base bias and have to be re-evaluated by experiments or the application on independent data sets in the future (compare ''results'').

This work would not have been possible without a large, freely available data base. This has been the ASHRAE RP-884 Adaptive Model Project- Data, processed and placed online by Professor Richard de Dear of the MacQuarie University Australia [4].

Processing the Fanger Data

The raw data for the distribution of the AHSRAE votes for a single PMV can be found in Fanger [1, Table 14]. It shows the relative distribution of votes for PMVs between −2.15 and 2.02 tabulated by the temperature of the related experimental setting. As expected, the calculated PMVs are decimal numbers and not absolutely regularly distributed (see Table 1).

Table 1. Distribution of ASHRAE votes for PMV (PMV calculated)

	ASHRAE votes						
PMV	−3	−2	−1	0	1	2	3
−3.00	100.0	0.0	0.0	0.0	0.0	0.0	0.0
−2.15	42.4	36.3	16.2	3.8	1.3		
−1.99	28.8	48.7	15.0	7.5			
−1.42	12.5	30.5	45.2	10.4	1.4		
−1.25	8.8	33.7	31.2	26.3			
−0.83	5.6	11.1	47.2	33.3	2.1	0.7	
−0.19		3.8	22.5	62.5	11.2		
0.00	0.7	2.1	18.1	57.5	18.8	2.8	
0.45			3.8	57.5	31.2	5.0	2.5
0.70			4.2	38.8	41.0	14.6	1.4
1.35				17.5	41.3	30.0	11.2
1.09				25.0	45.0	26.3	3.7
1.60				8.8	38.7	36.3	16.2
2.02				5.0	16.3	50.0	28.7
3.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0

Even though the PMV scale comprises −3 and + 3 it is – due to the distribution of votes – unlikely to obtain the same mean ASHRAE vote for a group of persons. As the ASHRAE scale does not extend beyond −3 and +3 a mean ASHRAE vote of −3/3 necessitates a 100% vote for −3/3. Nevertheless it is important for this work to know how the distribution of votes beyond the tabled data could look like. Further on, it is desirable to know the distribution of ASHRAE votes for other decimal PMVs.

For this reason, functions of the type

$$a \cdot e^{b \cdot \mathrm{PMV}^2 + c \cdot \mathrm{PMV}^3 + d \cdot \mathrm{PMV}^4}$$

have been developed to fit the data points of the columns of the table. This finally leads to seven functions $f_{\mathrm{ASHRAE}}(\mathrm{PMV})$ (one for each ASHRAE category) which yield the vote fraction of the single ASHRAE categories for any (decimal) PMV. For the fitting procedure the table was extended by adding a hypothetical vote fraction for +3 and −3 (100 or 0). Further on, the fit was balanced in order to obtain a symmetrical distribution for symmetrical ASHRAE categories.

For further processing of the data and joining with the ASHRAE data the functions have been tabled at steps of dPMV = 0.1. Since slight deviations from 100% occurred, every row has been finally normalized to 100%. The resulting curves compared to the original data points can be seen in Figure 1.

Analyzing the ASHRAE Data

ASHRAE Data Set Preparation

The data set that was used to analyze the correlation between ASHRAE vote and Preference is the ASHRAE RP-884 Adaptive Model Project- Data. It has been compiled, processed and placed online by Professor Richard de Dear of the MacQuarie University Australia [4].

Instead of using the complete data set a reduced one was compiled: Data sets without Preference votes or with an obviously different scaling of the Preference votes were omitted. From the remaining data sets only those observations were taken that fulfilled all of the following criteria:

- The ASHRAE votes are integer numbers, not decimal numbers,
- the calculated PMV is within the range of −3, . . . , 3,
- the data contains information about gender, building type, outside temperature and age.

By this, the number of useful observations was reduced to 13,789. The data now comprised observations from 147 different buildings (mechanically ventilated and cooled (HVAC) and naturally ventilated (NV), mainly office buildings) in different locations with different climatic conditions (Bangkok, Brisbane, Darwin, Honolulu, Kalgoorlie, Karachi, Melbourne, Montreal, Multan, Ottawa, Oxford, Peshawar, Quetta, Saidu Sharif, Townsville).

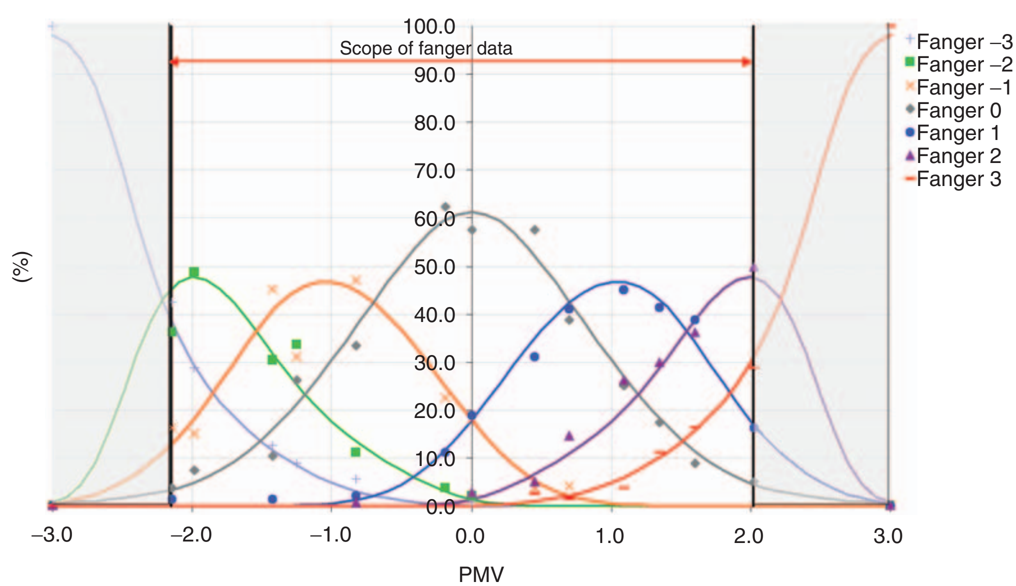

Fig. 1. Distribution of ASHRAE votes over PMV.

Table 2. Cross tabulation of ASHRAE votes and Preference votes, number of observations for the total data set

	Cooler	No change	Warmer	Σ	mPREFvote
−3	4	41	488	533	2.91
−2	57	397	647	1101	2.54
−1	210	1420	967	2597	2.29
0	804	4416	262	5482	1.90
1	1948	686	32	2666	1.28
2	1010	97	11	1118	1.11
3	270	21	1	292	1.08
Σ	4303	7078	2408		
mASHvote	1.03	−0.20	−1.52		

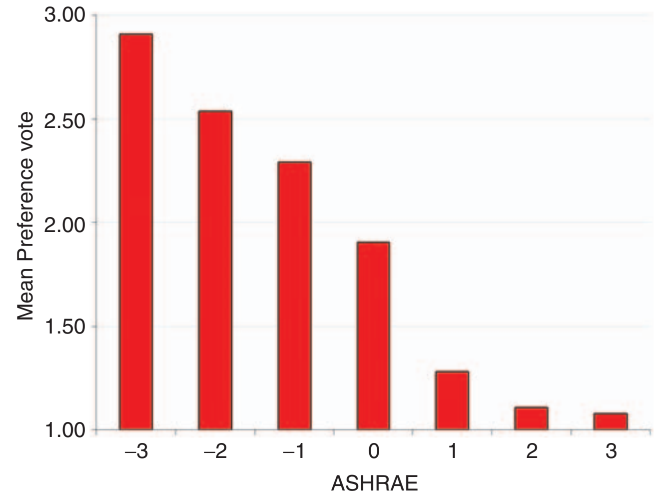

Fig. 2. Mean Preference vote for ASHRAE category.

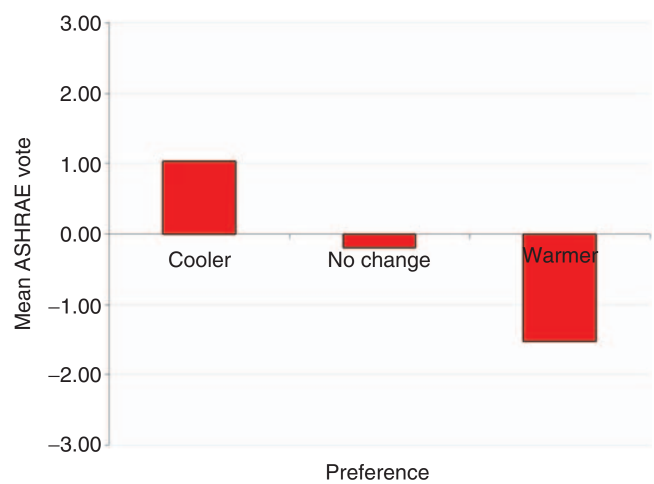

Fig. 3. Mean ASHRAE vote for Preference category.

The correlation was analyzed on the one hand for the complete data without any differentiation. On the other hand the data was additionally split into the factors "building type", "gender", "age", "outdoor temperature", and "indoor conditions" to analyze dependencies to improve the predictive quality of the PPD*. The attribute "age" consisted of 10 intervals ranging from 14 yrs to 63 yrs whereas the attribute "outdoor temperature" consisted of 8 intervals (−13.5 to 32.5°C). As representative for the indoor conditions the PMV (or rather a corrected PMV_{corr}, see below) was taken and split into seven intervals. In all cases the size of the intervals was chosen in such a way that they contained an approximately equal amount of observations (consequently they were not equidistant).

A part of the analysis was the calculation of the "mean Preference vote" for each ASHRAE category. This is carried out equivalently to the calculation of the mean ASHRAE vote. The numerical scale for Preference comprises 1 ("prefer cooler"), 2 ("no change") and 3 ("prefer warmer").

Correlation Between ASHRAE Votes and McIntyre Votes

Without Factor Differentiation

The correlation between the ASHRAE vote and the thermal Preference is shown in Table 2. The table can be read either vertically or horizontally. For each ASHRAE category the mean Preference vote (mPREFvote), and for each Preference category the mean ASHRAE vote (mASHvote) was calculated. The results are shown in Figures 2 and 3.

These figures show on the one hand, that on average people are voting with about −1/1 when they prefer a change. On the other hand, they show that there is not only a distribution for each Preference category but all in all a shift to negative ASHRAE votes.

The graphical representation of the mean Preference vote for each ASHRAE category is shown in Figure 2. It gives information about the dissatisfaction quality of the single ASHRAE votes. There is the same shift as presented before: People who are voting neutral have the tendency to prefer cooler conditions (below 2), further on, the curve is leveling off at 2/3. Due to the shift to the preference of cooler conditions the categories 2 and 3 obviously have about the same meaning concerning dissatisfaction. This shows, that the difference in thermal quality between the single ASHRAE categories is obviously not as equidistant as suggested by the numerical values.

Table 3. Vertical, relative distribution of votes

	Cooler	No change	Warmer
−3	0.09	0.58	20.27
−2	1.32	5.61	26.87
−1	4.88	20.06	40.16
0	18.68	62.39	10.88
1	45.27	9.69	1.33
2	23.47	1.37	0.46
3	6.27	0.30	0.04

Table 4. Horizontal, relative distribution of votes

	Cooler	No change	Warmer
−3	0.75	7.69	**91.56**
−2	5.18	36.06	**58.76**
−1	8.09	**54.68**	37.24
0	14.67	**80.55**	4.78
1	**73.07**	25.73	1.20
2	**90.34**	8.68	0.98
3	**92.47**	7.19	0.34

The main point of this paper however, is to show that the classical assumption of Gagge/Fanger (i.e., persons who vote with −1/0/1 can be assumed to be thermally satisfied and the others cannot) is too crude and that this is not verified by the analyzed data set: people who are voting with "neutral"/0, −1, or 1 on the ASHRAE scale are not necessarily satisfied with their thermal conditions but can – in some cases – prefer a change (either warmer or cooler on the McIntyre scale). At the same time, people who prefer no change in their conditions (on the McIntyre scale) are not necessarily voting with "neutral"/0, −1, or 1 on the ASHRAE scale. Tables 3 and 4 show the relative horizontal and vertical distribution of the votes. In Table 4, the maximum values are bold. It shows in an exemplary manner that generally assuming satisfaction for those people who are voting 1 on the ASHRAE scale is wrong. Instead, the majority would prefer cooler conditions (prefer cooler on the McIntyre scale) under these conditions and thus are not satisfied.

With Factor Differentiation

The data Tables 3 and 4 show an asymmetrical distribution, vertically (for a constant preference vote) as well as horizontally (for a constant ASHRAE vote). This raises the question whether there are dependencies on certain factors or not.

As mentioned above the data has been further differentiated and analyzed as follows.

- indoor conditions, factor: PMV_{corr}, levels: −1.35, −0.53, −0.3, −0.1, 0.1, 0.4, 1.23 as interval center values,
- factor: outdoor temperature, levels: −13.5, 4.5, 13, 18, 23, 26, 28.5, 32.5 as interval center values,
- factor: building type, levels: HVAC, NV,
- factor: gender, levels: male, female,
- factor: age, levels: 14.5, 17, 21, 25, 28.5, 32.5, 36, 41, 47.5, 62.5 years as interval center values.

Normally these dependencies are analyzed for comparable, objective thermal boundary conditions. A question could be, whether older people are voting differently for comparable thermal conditions, activity and clothing than younger people do.

In this case, however, it is not the thermal condition that is used as background. Instead, as explained above, the Preference votes were examined for all ASHRAE categories separately (so that the ASHRAE category is the background). Additionally, vice versa, the ASHRAE votes were analyzed for constant Preference votes. Both are then plotted against the factors mentioned above.

Each of the tables showing the relative distribution of votes consists of 21 cells. If all the data is split into a number of levels it might happen that in some cases there are too few observations in a row or a column to calculate the mean vote. The lowest acceptable number of observations was arbitrarily set to 15 for rows and to 35 for columns. If this requirement is not met the value is not assessed which then results in a missing spot in the graphical representation. Further on, the necessary amount of data for the calculation of the mean votes makes it difficult to carry out any multi-factor analysis (e.g., the dependence on outdoor temperature for different age groups). Instead, only 1-factor calculations with a qualitative control of the other factors were carried out.

All dependencies of the McIntyre vote on the listed factors were checked for significance on the basis of a 1-factor analysis of variance (ANOVA). The results are summarized in Table 5. It can be seen, that the differences between the factors are highly significant but do not necessarily explain a great portion of the variations.

Differing Indoor Conditions

First of all, the correlation of the ASHRAE vote and the Preference vote was analyzed for varying indoor conditions. The calculated PMV value was taken as representative of the indoor conditions since it is the most complete representation of the thermal conditions relevant for an individual. Later on we will show that taking the PMV instead of temperature has great advantages concerning interpretation of the data.

Humphreys [3] has shown that the PMV does not predict the mean ASHRAE vote precisely enough for this data set. As the improvement of the prediction of dissatisfaction is only possible on the basis of an index that predicts the mean ASHRAE vote reliably we have adjusted for this error. This separates the effect found by Humphreys [3] from the potential errors of the method we propose. The PMV was corrected by a very rough-and-ready method. It must be clear, that this correction does not aim for a scientific explanation of the deviation of the PMV from the mean ASHRAE vote. But with a view to the final goal of this paper, which is to develop an improved PPD concept, it is simply necessary to have a better numerical predictor of the mean ASHRAE vote available.

Table 5. *F*, *p*, and R^2 values for the different factors (1-factor ANOVA)

Factor	Building type	Gender	Age	PMV_{corr}	Outdoor temperature
F	144.47	26.44	8.82	511.48	312.20
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R^2	0.01	0.002	0.006	0.18	0.14

In order to correct the PMV, the PMV was split into intervals of the size 1 (0.5 at the borders) with integer values as interval center. From all ASHRAE votes occurring within these single PMV categories the mean ASHRAE vote was calculated and compared against the interval center of the PMV category (see Figure 4). The difference (deviation) was linearly fitted and used as a numerical correction of the PMV. This corrected the best part of the error (see Figure 5) and for the rest of the analysis the PMV_{corr} was used.

Figure 6 shows the mean ASHRAE vote, separated by the preferences “warmer”, “no change”, and “colder”. It is striking, that with warmer indoor conditions the mean ASHRAE vote for each preference category increases. This suggests that there is some kind of adaptation process of preference to the indoor condition taking place as it would be plausible on first sight that people will accept cooler conditions when adapted to cool conditions and will accept warmer conditions when adapted to warm conditions. It is, however, important to note, that it is not easy to track adaptation processes by analyzing these kind

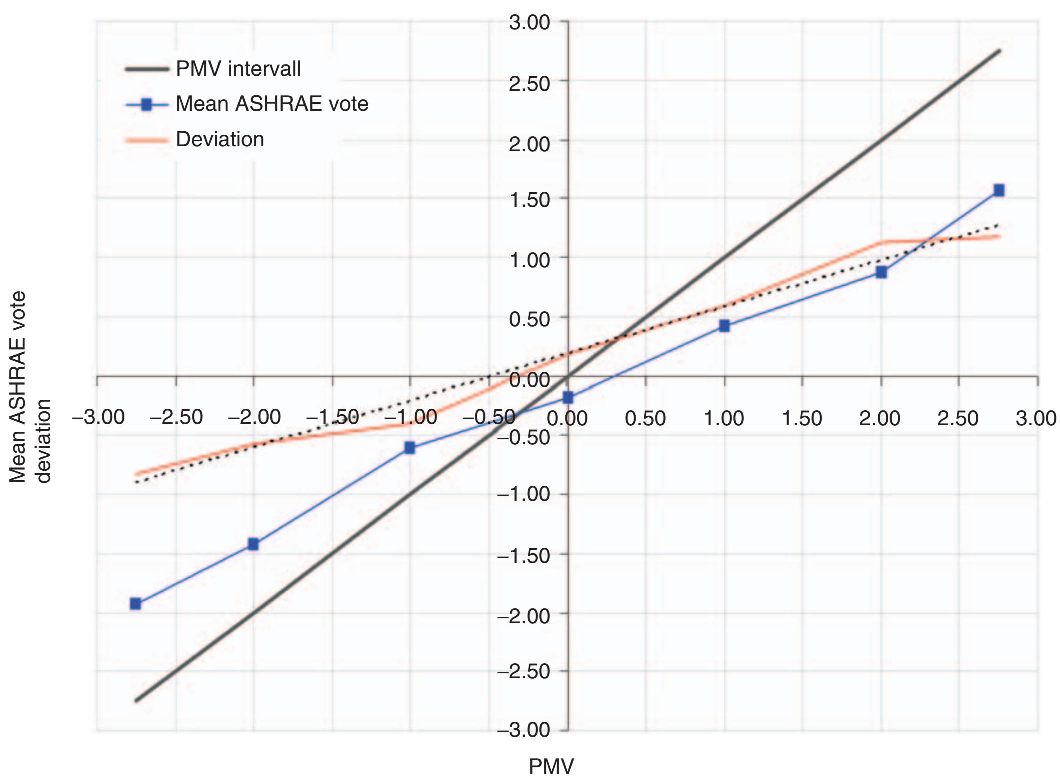

Fig. 4. Deviation of the mean ASHRAE vote from PMV.

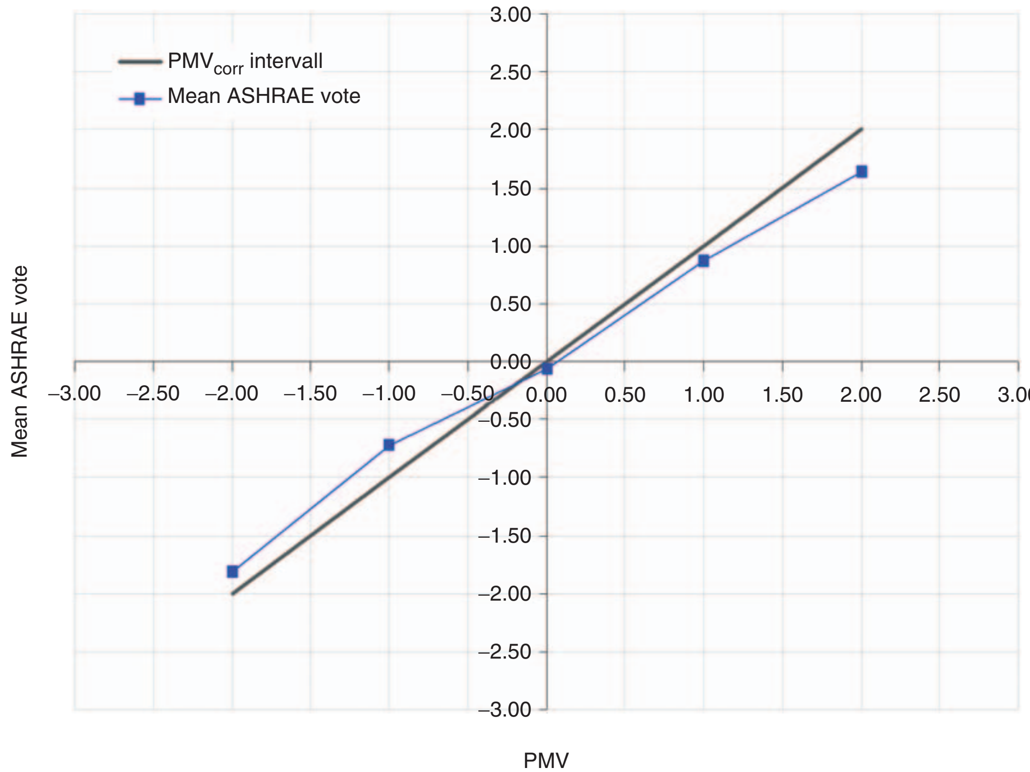

Fig. 5. Deviation of the mean ASHRAE vote from PMV_{corr}.

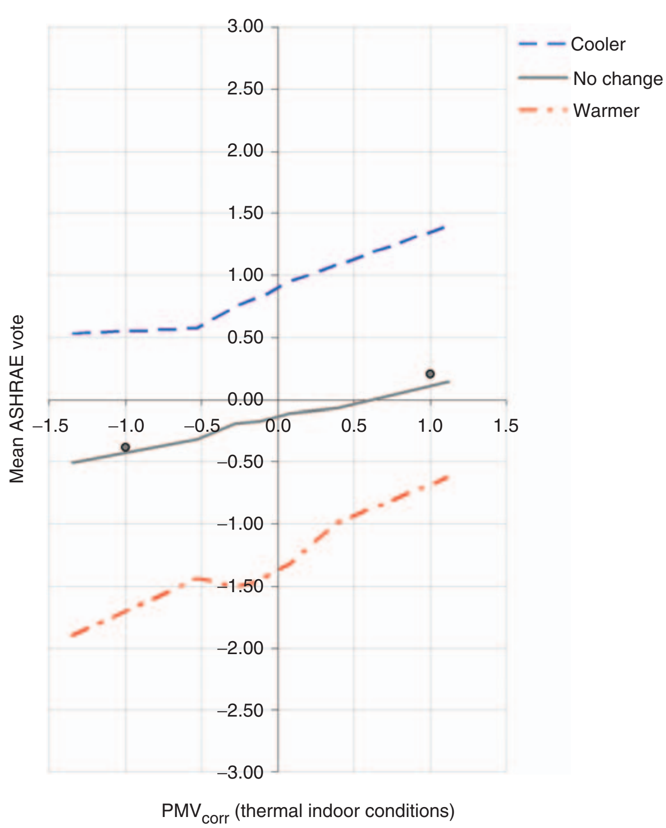

Fig. 6. Mean ASHRAE vote for Preference category –Indoor conditions.

of data sets. Those, who are voting with "no change" in cold conditions, e.g., are simply neither the same individuals nor the same "thermal type" of person as those, who are voting with "no change" in warm conditions.

Actually, the observed effect can basically be attributed to the change of the distribution of votes. If the distribution of votes for the "no change" preference of the full data is looked at ("base distribution", see Table 3), it can be seen, that the majority of people prefer neutral conditions. There are however people who prefer conditions that differ from neutral, i.e., cooler or warmer. Therefore, if a person senses cooler conditions than neutral, say −1 on the ASHRAE scale, while preferring no change (i.e., the person is thermally satisfied), we term this person "cool preferring". Otherwise, if a person senses warmer than neutral conditions, say 1, while preferring no change, we term this person "warm preferring".

Additionally, the Fanger data shows a distribution of ASHRAE votes around the calculated PMV. For PMV ± 1, e.g., the main part of votes occur at ±1 but there are additional votes that deviate from this (see Figure 1). If both curves (Fanger distribution and "base distribution" for the preference) are now superimposed the resulting curve shows a maximum that deviates from the distribution of the original "no change" base

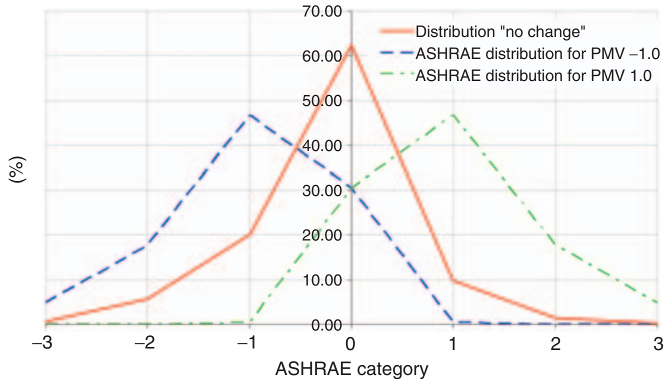

Fig. 7. Superimposition of "no change, total data set" and PMV −1/1 distribution.

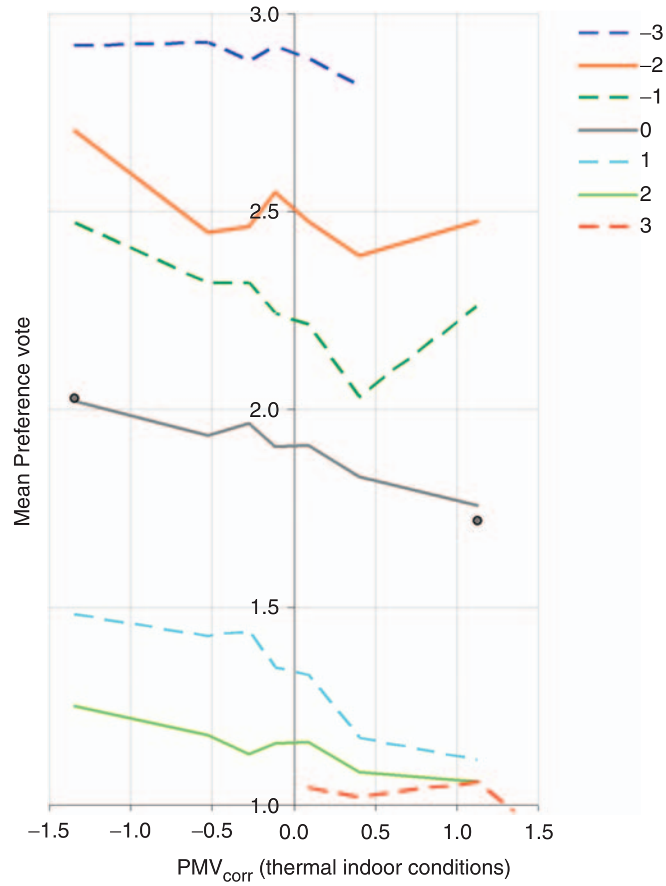

Fig. 8. Mean Preference vote for ASHRAE category – indoor conditions.

distribution (Figure 7). Among the "no change" votes the "cool preferring" votes (for −1) or, respectively, the "warm preferring" votes (for 1) are pronounced for conditions deviating from neutral. If the mean ASHRAE vote is calculated for the resulting, superimposed curve this results in −0.39 (for PMV −1) and 0.21 (for PMV 1). These values are shown in Figure 6 as grey dots for the "no change" category. This shows, that the shifting of the ASHRAE distribution for a PMV in combination with a constant base distribution for "no change" is a good explanation for the gradient of the curves: in cooler than neutral conditions those who prefer cooler conditions are in the majority and in warmer than neutral conditions those who prefer warm conditions are in the majority of those voting with "no change".

Figure 8 shows the mean Preference over indoor conditions for all ASHRAE categories. There obviously exists a negative gradient which indicates, that with warmer conditions (positive PMV_{corr}) one and the same ASHRAE category represents warmer sensations (tendency to "prefer cooler" with warmer conditions) on average. The effect shown is basically the same as before, even though it is not based on an established system of figures: Analogously to the PMV, an index Predicted Preference Mean Vote (PPMV) can be used that represents a certain distribution of actual Preference votes (1, 2, and 3, "cooler", "no change", and "warmer"). This PPMV index and the correlated distribution was calculated for all PMV_{corr}- intervals. Then, in the same manner as before, the distribution of Preference votes for "neutral" of the total data set ("base distribution") was superimposed with the distribution of PPMV 2.38 (which correlates with a PMV_{corr} of −1.35) and PPMV 1.38 (which correlates with a PMV_{corr} of 1.125), Figure 9. This resulted in a Preference mean vote of 2.03 and 1.72. Both values are marked by a grey dot in Figure 8 for neutral ASHRAE votes. This shows, that the effect of the sloping preference curves can be explained by the distribution of votes.

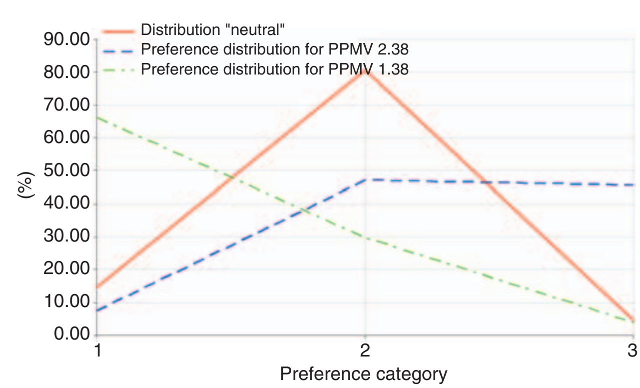

Fig. 9. Superimposition of "neutral, total data set" and PPrefMV 2.38/1.38 distribution.

With varying thermal conditions, the number of people voting for a certain ASHRAE category changes

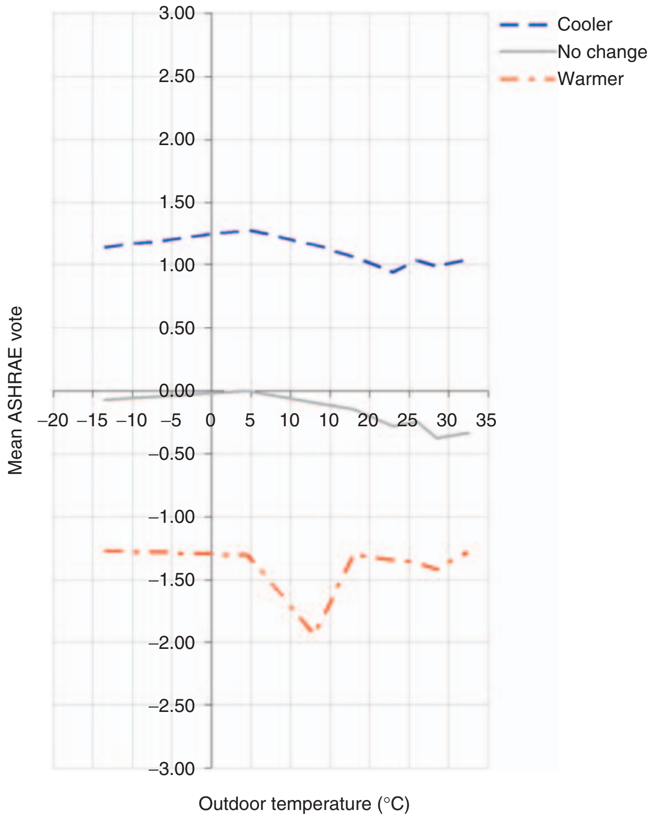

Fig. 10. Mean ASHRAE vote for Preference category – outdoor temperature.

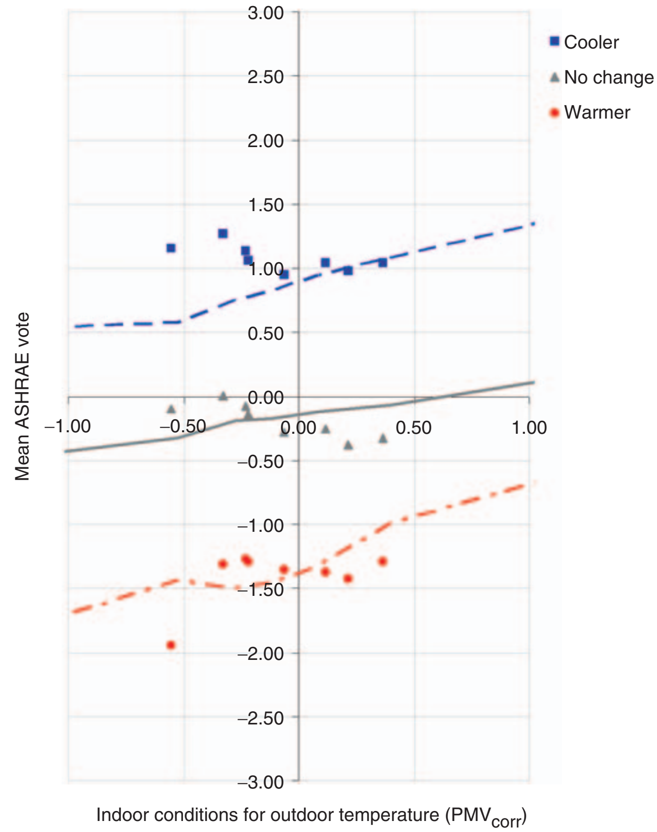

Fig. 11. Mean ASHRAE vote for Preference category – outdoor temperature.

(see above, Figure 1). With reference to the Fanger data, the percentage of people voting "neutral" under a PMV-1 condition is about 30%, increasing to about 60% for a PMV-0 condition and then falling again to about 30% under a PMV-1 condition. This shift in the magnitude of votes seems to play a minor role for the base distribution of an ASHRAE category (e.g., "neutral"). However, it is interesting to note, that those who are voting with "neutral" under PMV-1 conditions are warm sensing (warmer than the average) but have a tendency to prefer warmer conditions and those who are voting with "neutral" under PMV-1 conditions are cold sensing (colder than the average) but show a tendency to prefer cooler conditions.

Differing Average Outdoor Temperatures on the Day of Measurement

The influence of the average outdoor temperature on the day of measurement on the mean ASHRAE vote and the mean Preference vote was also analyzed.

Figure 10 – the mean ASHRAE vote for each of the preference categories – shows a fairly constant distribution of mean ASHRAE votes over all outdoor conditions. There is only a slight tendency of the graphs to fall. Additionally, the lines display a certain up and down over outdoor conditions, but the peaks are not characteristically distributed. All in all it could be claimed at first sight, that there exists no systematic dependency on the outdoor temperature.

However, there is a positive correlation between outdoor temperature and indoor conditions. Therefore, for all outdoor temperature intervals the PMV_{corr} – as representative of the correlated indoor conditions – was calculated and the mean ASHRAE vote for the Preference categories was then plotted over those indoor conditions (Figure 11, dots). The comparison with the graphs of the mean ASHRAE votes over indoor conditions of the previous chapter (lines) shows a remarkable difference between both, with the dots representing fairly constant mean ASHRAE votes. This difference is obviously the effect of the outdoor temperature on the base distribution. To counteract the shift of ASHRAE votes for varying PMV the maximum of the base distribution has to be shifted to the other direction. Consequently, people on the one hand tend to prefer warmer conditions

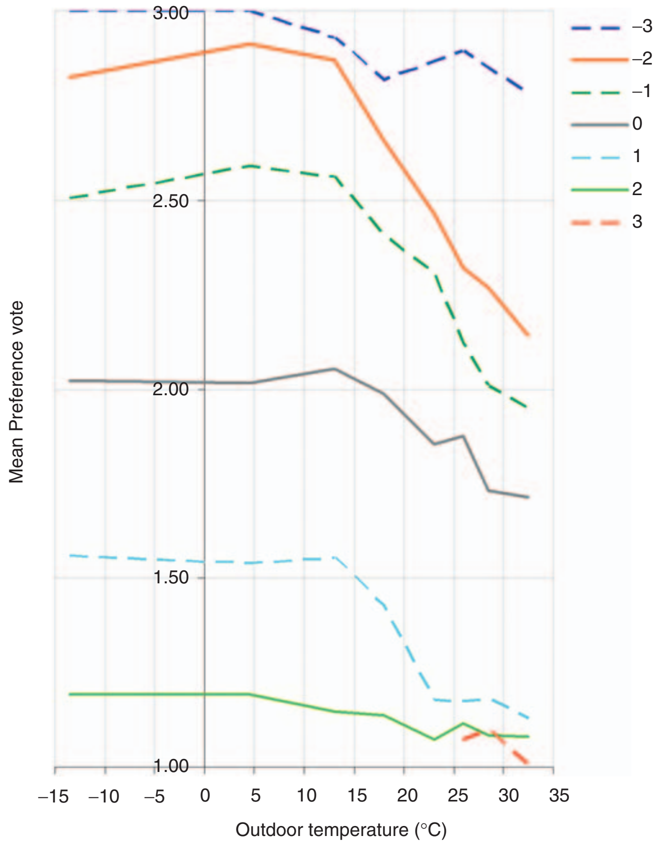

Fig. 12. Mean Preference vote for ASHRAE category – outdoor temperature.

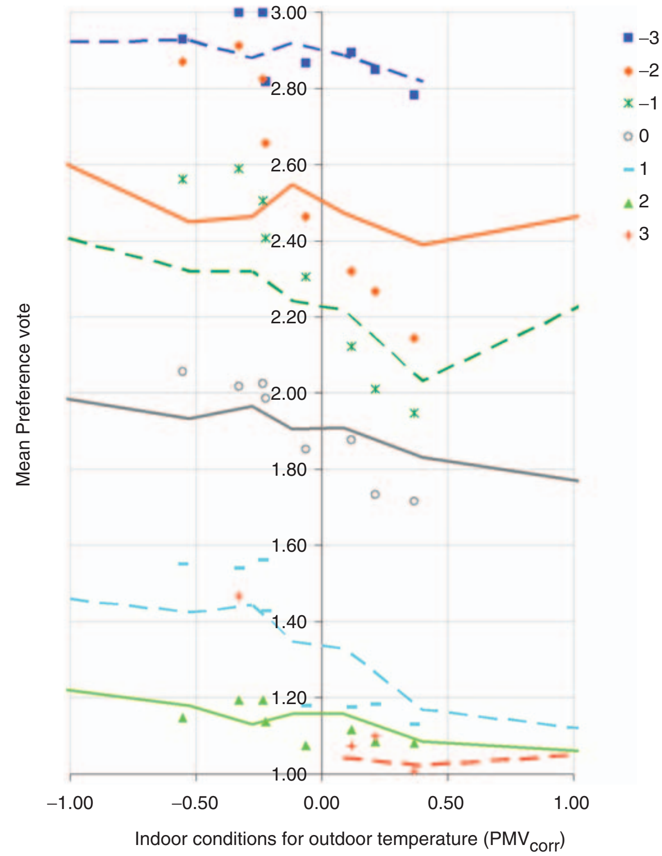

Fig. 13. Mean Preference vote for ASHRAE category – outdoor temperature.

when outside temperatures are low and on the other hand tend to prefer cooler conditions when the outside temperatures are higher. If the thermal sensation itself is subject to this change or the description of basically similar thermal states is not clear (compare Humphreys [5]).

Figure 12 shows the mean Preference vote for each ASHRAE category over outdoor temperature. The lines are fairly constant below an outdoor temperature of about 10–15°C. Above this outdoor temperature mark – so at a point at which increasing outdoor temperatures cause increasing indoor temperatures – the lines drop and therefore represent the preference of cooler conditions. Plotting the mean Preference votes over the indoor conditions (PMV_{corr}) at the outdoor temperature interval (Figure 13, dots) and comparing them against the graphs of the previous chapter (indoor conditions) shows, that the slope is steeper now. Again, this difference makes up the effect of the outdoor conditions on the preference and agrees with the above. With increasing outdoor temperature a constant ASHRAE vote is interpreted as becoming warmer. With decreasing outdoor temperature a constant ASHRAE vote is interpreted as becoming cooler.

Differing Building Types (HVAC vs. NV)

The average thermal conditions in both differently ventilated types of building differ, with the NV buildings having slightly warmer conditions than the HVAC buildings. This is accepted since the differences are not large ($PMV_{corr,NV} = 0.11$, $PMV_{corr,HVAC} = -0.25$). The difference between the outdoor temperatures is 5°C (22°C for NV buildings, 17°C for HVAC buildings). This might have an effect but the findings show a result not related to the effect of the outdoor temperature. This difference is therefore also accepted without correction.

Figure 14 shows the mean ASHRAE vote for the different Preference categories. There are two different representations, one showing the graphs for the Preference categories (3 curves, upper *x*-axis) and the other one showing the graphs for the building types (2 curves, lower *x*-axis). The figure shows that the range of acceptable conditions seems to be narrower for HVAC buildings than

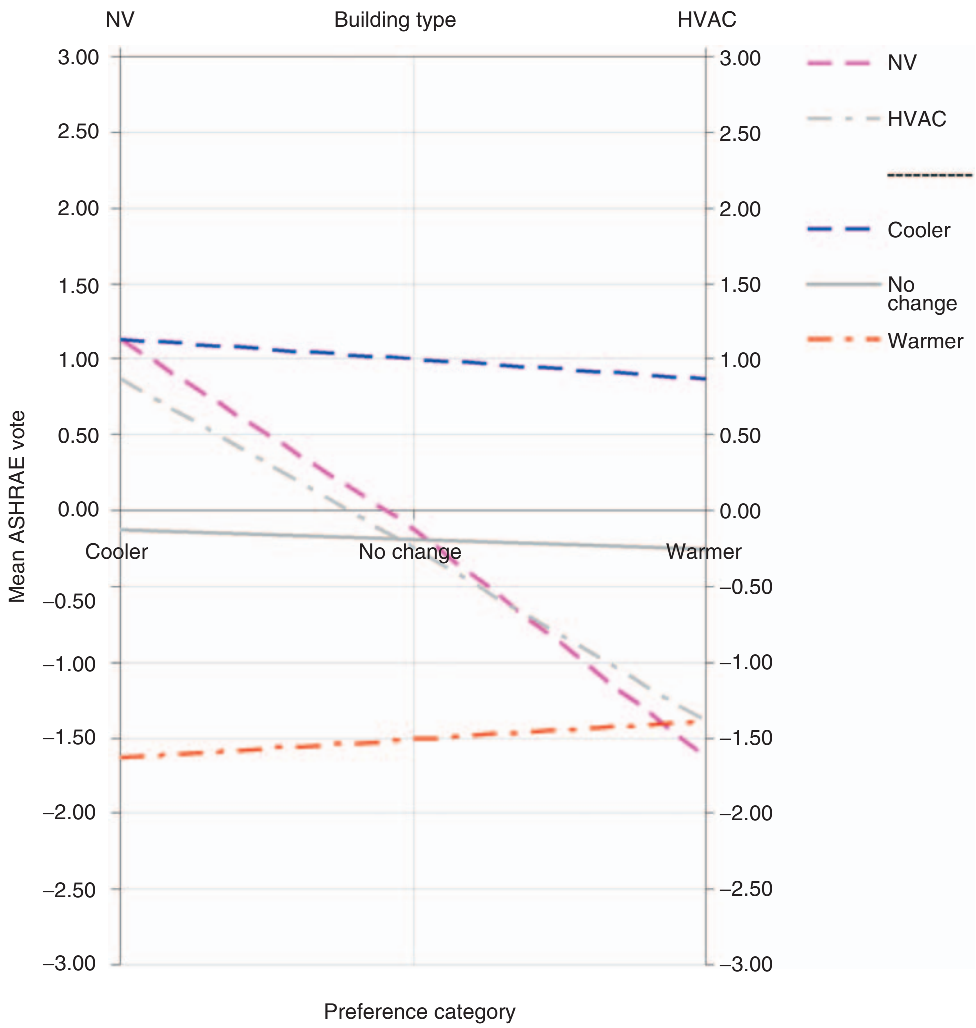

Fig. 14. Mean ASHRAE vote for Preference category – HVAC vs NV.

for NV buildings (the mean ASHRAE votes for "cooler" and "warmer" are closer to neutral for HVAC buildings).

Figure 15 shows the Mean Preference vote. The first group of graphs (two graphs, one for NV and another for HVAC) shows the mean preference vote over ASHRAE categories (lower x-axis). The second group of graphs (six graphs for the ASHRAE categories) shows the differences of the mean Preference between the two types of buildings (upper x-axis).

It is obvious that the NV-curve (pink dotted) tends to more extreme Preference votes for both, warm and cold conditions (except for the ASHRAE −3 category). The mean Preference of those occupants in NV buildings voting with 2/3 is therefore nearer to the absolute "prefer cooler" preference than the mean preference of HVAC occupants. It is the same with the cool conditions: Having an ASHRAE −2 vote, more occupants of NV buildings prefer a change of the situation than HVAC occupants. The results therefore show the tendency that people seem to be less satisfied with extreme conditions in NV buildings (represented as a clearer preference for a change) than in HVAC buildings. This seems to contradict the above statement.

Maybe "acceptability" is not the only dimension for the interpretation of the difference. If the horizontal distribution of votes (so for each ASHRAE category) is viewed (Tables 6 and 7), it can be seen, that the distribution of Preference for extreme conditions (ASHRAE ±3, ±2) is sharper for NV occupants than for HVAC occupants. This means, there are more people voting irrationally ("prefer warmer" in warm conditions and "prefer cooler" in cold conditions) in HVAC than in NV buildings which finally leads to higher absolute mean Preference votes among NV occupants.

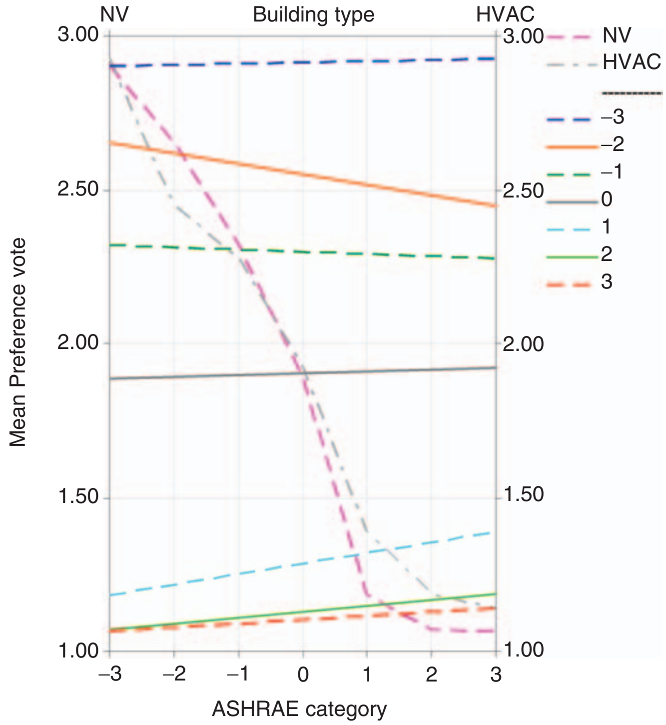

Fig. 15. Mean Preference vote for ASHRAE category – HVAC vs NV.

Table 6. Relative horizontal distribution of votes for HVAC buildings

	Cooler	No change	Warmer
−3	1.47	4.41	**94.12**
−2	5.71	43.81	**50.48**
−1	6.62	**59.08**	34.30
0	10.38	**87.19**	2.43
1	**62.80**	35.39	1.82
2	**83.29**	14.76	1.95
3	**88.00**	10.00	2.00

Table 7. Relative horizontal distribution of votes for NV buildings

	Cooler	No change	Warmer
−3	0.50	8.82	**90.68**
−2	4.46	25.69	**69.85**
−1	10.82	**46.47**	42.72
0	18.17	**75.13**	6.70
1	**82.36**	17.00	0.64
2	**93.68**	5.80	0.53
3	**93.39**	6.61	0.00

A possible interpretation is, that NV occupants have a better intuitive understanding of their local climate and are therefore more distinctive and clear in their reactions to it. Contrary to this a certain percentage of HVAC occupants show an irrational or less concise behavior concerning their preference. As they do not get control over their environment they might not be as competent in judging their conditions as NV occupants are. The assumption, that NV occupants accept more extreme conditions than HVAC occupants solely due to the psychological effect that they have control might not be the full truth. By gaining control they can develop a better understanding of their environment which might lead to a clearer reaction to it. Apart from "acceptability", "ability" could play a role.

Difference Between Genders

Both, the indoor conditions and the outdoor conditions are on average comparable for the male and the female group ($PMV_{corr,\ male} = -0.07$, $PMV_{corr,female} = -0.06$, outside temperature for both 19.9°C). Age differs by five years (male group: 33.5 yrs, female group: 28 yrs).

Figure 16 shows only a small difference for the mean ASHRAE vote for the different preferences. Only in warm conditions ("prefer cooler") females tend to accept slightly more extreme conditions. Figure 17 however, shows that the "female" preference line is consistently (over all ASHRAE categories) shifted upwards compared to the "male" line. This indicates the general preference of warmer conditions for females, which is more pronounced for extreme conditions and less pronounced for moderate conditions. Therefore, in extremely cold conditions (−3) females have a higher preference for warmth (nearer to a mean Preference of 3, "warmer") and in extremely warm conditions they have a lower preference for cold compared to males.

Differing Age Groups

The mean ASHRAE votes for the three preference categories are fairly constant over age (Figure 18), except for the lowest age intervals (14–21). For these intervals the ASHRAE votes are on average about 0.4 scale points lower than for the rest. For all intervals the indoor conditions were comparable (PMV_{corr} ranging from −0.16 to 0.06), the outside temperatures however were higher for the younger than for the older ($T_{outside,\ younger} = 25$°C, $T_{outside,\ older} = 17.5$°C). The difference in outside temperature, however, is not sufficient to explain the difference of the mean ASHRAE votes, especially as the indoor conditions for both age groups was almost the same ($PMV_{corr,\ younger} = -0.04$, $PMV_{corr,\ older} = -0.07$). Therefore, the deviation of the total mean ASHRAE vote from the PMV_{corr} for all age intervals was calculated

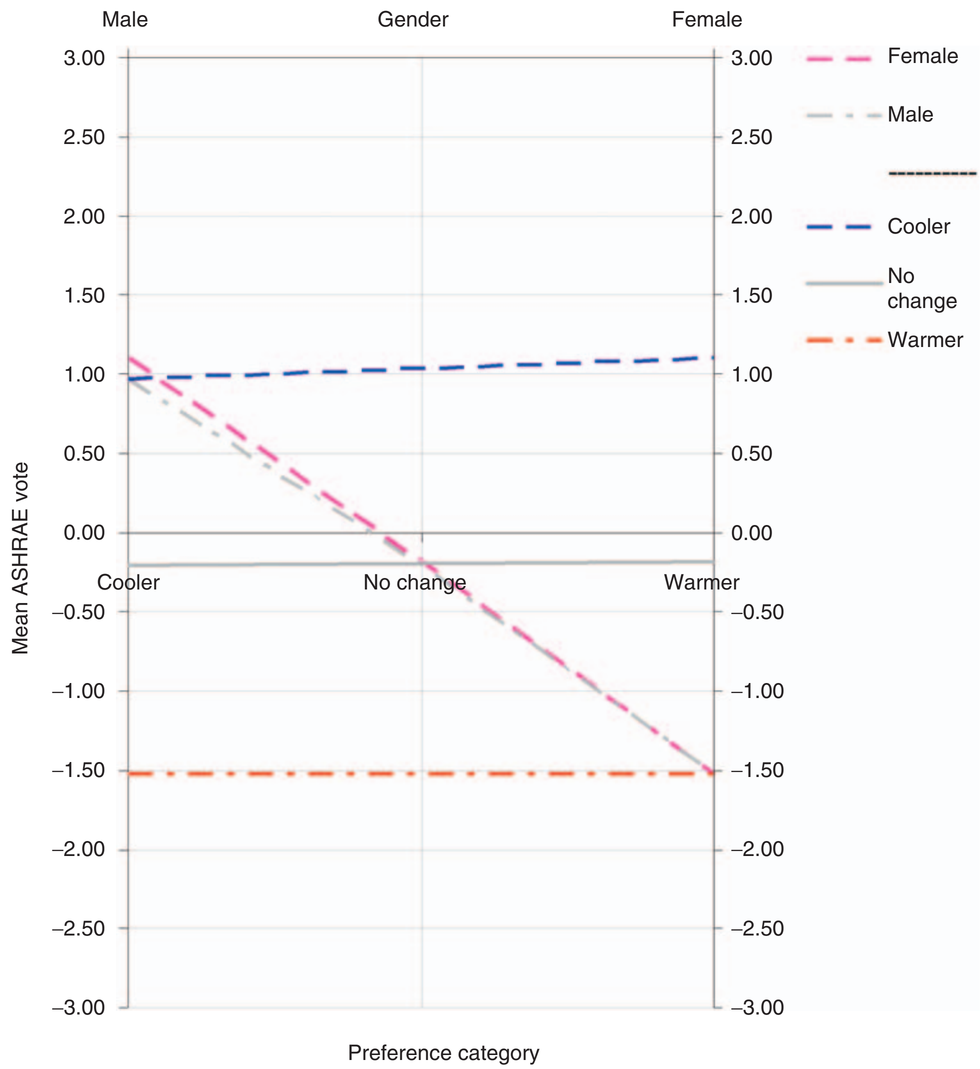

Fig. 16. Mean ASHRAE vote for Preference category – male vs female.

and plotted in Figure 18. It shows, that there is obviously a general deviation for the younger age group, who are interpreting one and the same thermal condition as cooler compared to older people. This is caused by a very large proportion of votes for ASHRAE −1 and ASHRAE −2 for all Preference categories of the young compared to the old.

The special role of ASHRAE −2 and ASHRAE −1 can also be found in Figure 19. This figure shows a distinct drop of the mean Preference vote for these ASHRAE categories for younger people compared to the old. This means, that on average, younger people are comparably more satisfied when voting with ASHRAE −2/−1. Concerning satisfaction, this is counteracting the cold estimation of the thermal conditions. Younger people may sense certain conditions as colder than older people do but are at the same time more content with these conditions than older people who are voting with the same ASHRAE vote.

Contradictions around the mean Preference is shown by the lines for ASHRAE 0 and ASHRAE-1 having the same value for the very young and by the ASHRAE 3 line being even higher (more acceptable) for the young than the ASHRAE 2 and 1 lines. If this is a true effect of age or something beyond the control of this examination is not clear. A possible interpretation would be, that the diversification of thermal sensation and thermal preference is higher among younger people due to the physical growth process and that in consequence very contradicting votes for different groups or individuals occur.

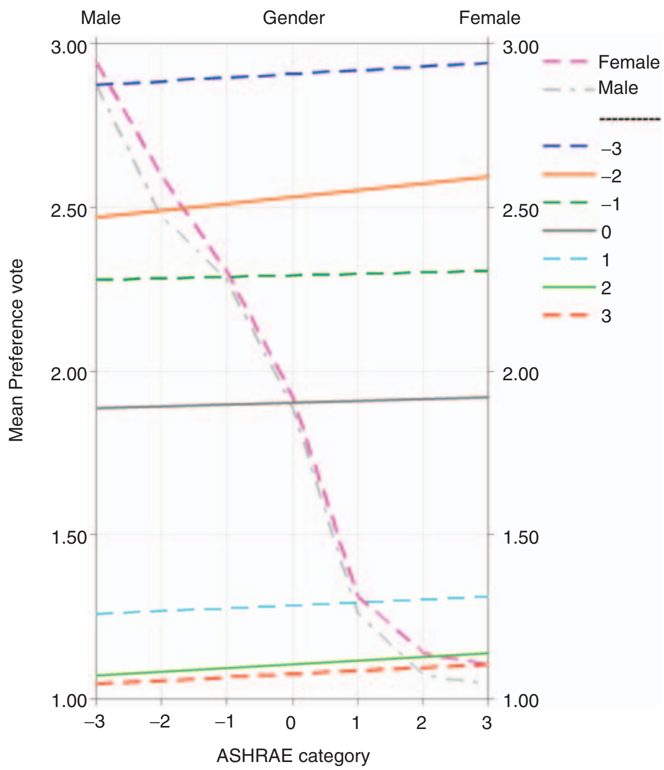

Fig. 17. Mean Preference vote for ASHRAE category – male vs female.

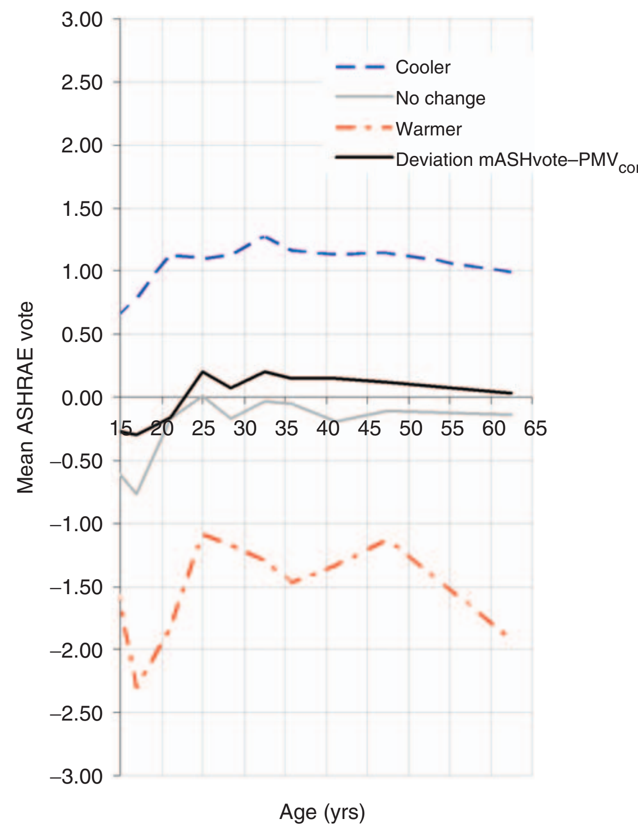

Fig. 18. Mean ASHRAE vote for Preference category – age.

Predicting Dissatisfaction on the Basis of the ASHRAE Vote

As described above, the classical PPD concept is based on the assumption, that people who are voting with ±2 and beyond are dissatisfied (compare [1], p.130 and [2]).

To compare the classical and the new concept of dissatisfaction the terms "being thermally dissatisfied" and "preferring a change of thermal conditions" are regarded as equal. On this basis it is hypothesized for the classical PPD concept that people who are voting between −1 and +1 prefer no change in their conditions whereas people who are voting with +2/+3 prefer cooler and people who are voting with −2/−3 prefer warmer conditions. Starting from this assumption the predictive quality of the classical PPD concept was analyzed by comparing the individual McIntyre vote of each observation of the data set with the preference calculated from the correlated individual ASHRAE vote.

The same was carried out with the PPD* concept. For each level of the described factors a table comparable to Table 4 exists, displaying the relative distribution of preference votes for each ASHRAE category. For the prediction, the individual vote was attributed to the correct level of the factor. Then simply that preference vote was taken, most of the individuals had voted for in this level and the relevant ASHRAE category. Since the factors "building type" and "gender" show no difference in the maximum of the preference votes compared to the total data they are not used here. The results are shown in Table 8.

It can be seen, that the predictive quality of the original PPD concept can be improved by correlating the ASHRAE and the McIntyre votes. The improvement is in the region of 15%. Differing between the single factors does not have a noteworthy effect on the quality. However, this does not make the differentiation dispensable. As shown above, this differentiation yields valuable information about the influence of some situation and individual factors. Nevertheless, the rough prediction system (namely to decide for the Preference vote with the maximum fraction) makes no differences between a vote fraction of 50% and 100% for a preference so that the differences between the levels are not fully transferred into the prediction system.

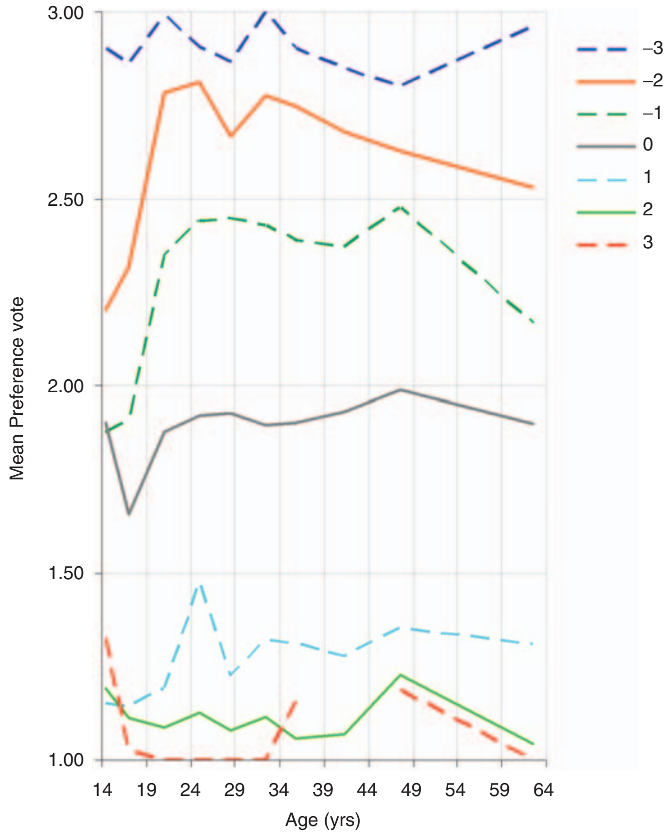

Fig. 19. Mean Preference vote for ASHRAE category – age.

Table 8. Improvement of the predictive quality, based on the individual ASHRAE vote

Factor	PPD, gagge	No differentiation	PMV_{corr}	Outdoor temperature	Age
Fraction of correct predictions	64.8%	74.0%	74.1%	75.6%	74.7%
Improvement relative to PPD	–	14.1%	14.3%	16.7%	15.2%

Joining the Fanger Data and the ASHRAE Data

Procedure

The distribution of ASHRAE votes for a defined PMV_{corr} value is known from Fangers experiments (see above). Both, the ASHRAE(PMV_{corr}) vote distribution and the Preference(ASHRAE) distribution can now be joined to obtain curves for the fraction of individuals being satisfied, cold dissatisfied or warm dissatisfied.

Table 9. Calculation example for PMV −2

	−3	−2	−1	0	1	2	3
Cooler	0.75	5.18	8.09	14.67	73.07	90.34	92.47
No change	7.69	36.06	54.68	80.55	25.73	8.68	7.19
Warmer	91.56	58.76	37.24	4.78	1.20	0.98	0.34
PMV_{corr} −2	0.299	0.477	0.177	0.047	0.000	0.000	0.000

The procedure is as follows (compare Table 9):

To determine the fraction of people who prefer cooler conditions under a certain PMV_{corr} condition, the ASHRAE distribution for the PMV_{corr} in question is multiplied cell by cell with the row for "cooler" and finally added up. The procedure is the same for the "no change" and the "warmer" preference.

Doing this for PMV_{corr} between −3 and 3 yields the following distribution (for the total data set) (Figure 20):

From the distribution shown in Figure 1 the fraction of dissatisfied persons based on the assumption of Gagge can be calculated, Figure 21.

There are two main differences: First of all, the distribution in Figure 20 is asymmetrical compared to the distribution of the classical PPD. It shows the shift of the "no change" curve to cooler conditions that has already been mentioned above. More important however is the fact, that the largest fraction of persons that can be satisfied in a thermal situation is around 70%, which is much less than the 95% of the PPD.

Predicting Dissatisfaction on the Basis of the PMV_{corr}

Curves similar to Figure 20 were produced for all levels of the analyzed factors. They are used to predict the preference on the basis of the PMV_{corr}. Again, the decision for one preference is reached by comparing the values of all curves at the PMV_{corr} in question and taking the maximum value. From this is clear, that only the shift of the intersection of the curves makes a difference for the prediction. The results are listed in Table 10.

The results show, that the predictive quality can be improved compared to the classical PPD concept. The improvement ranges between 8% and 13%. However, the total quality is still weak and does not reach 60%. This is probably due to the flatness of the preference curves (which is a characteristic of the distribution for most of the factors/levels) which show that in spite of the differentiation of some important factors there still exists a broad distribution of individual preferences. Differences between gender even slightly reduce the effectiveness of the concept compared to the prediction based on the total data set.

Due to the large amount of factors and levels that were analyzed here it is not possible to display each curve. Therefore these resulting curves have been fitted with the following equation:

$$\%(\text{preference}) = a \cdot e^{b\cdot PMV_{corr} + c\cdot PMV_{corr}^2 + d\cdot PMV_{corr}^3 + e\cdot PMV_{corr}^4 + f\cdot PMV_{corr}^5 + g\cdot PMV_{corr}^6}$$

The coefficients a to g for all levels and for each preference category are shown in Tables 11–16.

Sharper curves would lead to a clearer differentiability between satisfying and dissatisfying conditions. This could certainly be reached by differing between more factors or by carrying out multi-factor analysis with a sufficient number of observations (see above).

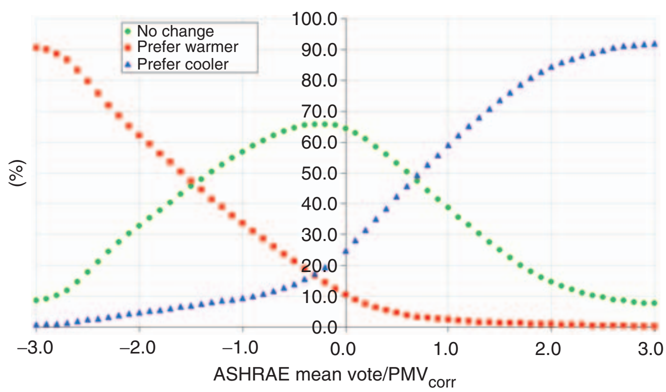

Fig. 20. ASHRAE mean vote/PMV_{corr} to MCI – total.

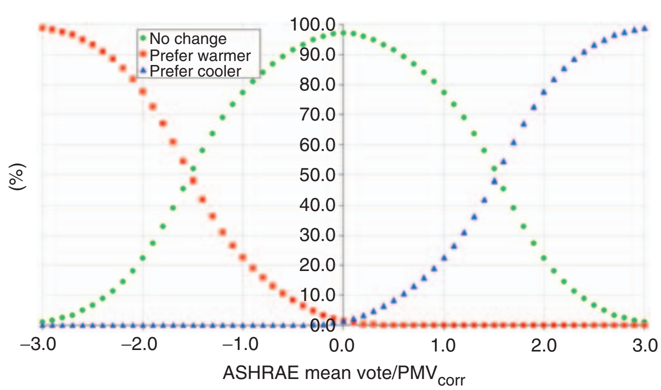

Fig. 21. ASHRAE mean vote/PMV_{corr} to MCI – Fanger/Gagge.

Summary and Future Work

Thermal dissatisfaction is closely related to the preference of conditions that are cooler or warmer then the present conditions. This preference can be expressed by the

Table 11. Coefficients for PMV to MCI – total

Prefer cooler	a	25.2472
	b	1.0558
	c	–0.0942
	d	–0.1417
	e	0.0230
	f	0.0138
	g	–0.0033
Prefer no change	a	63.8872
	b	–0.1753
	c	–0.3273
	d	–0.0262
	e	0.0204
	f	0.0054
	g	–0.0013
Prefer warmer	a	10.8205
	b	–1.4715
	c	–0.2508
	d	0.1385
	e	0.0558
	f	–0.0087
	g	–0.0040

Table 10. Improvement of the predictive quality, based on the PMV_{corr}

Factor	PPD	No differentiation	Gender	Building type	PMV_{corr}	Outdoor temperature	Age
Fraction of correct predictions	52.1%	56.8%	56.4%	57.6%	58.3%	59.0%	57.9%
Improvement relative to PPD	–	8.8%	8.2%	10.4%	11.8%	13.0%	11.0%

Table 12. Coefficients for PMV to MCI – building type

		Building type	
		HVAC	NV
Prefer cooler	a	20.4807	29.6351
	b	1.1210	0.9904
	c	−0.0708	−0.0998
	d	−0.1639	−0.1300
	e	0.0281	0.0181
	f	0.0142	0.0143
	g	−0.0035	−0.0033
Prefer no change	a	70.7664	57.3223
	b	−0.1234	−0.2016
	c	−0.2992	−0.3791
	d	−0.0324	−0.0187
	e	0.0256	0.0232
	f	0.0070	0.0044
	g	−0.0025	−0.0007
Prefer warmer	a	8.9527	13.0953
	b	−1.5526	−1.4326
	c	−0.1885	−0.3222
	d	0.2276	0.0580
	e	0.0790	0.0384
	f	−0.0147	−0.0009
	g	−0.0061	−0.0017

Table 13. Coefficients for PMV to MCI – gender

		Gender	
		Male	Female
Prefer cooler	a	26.1740	24.2175
	b	1.0255	1.0899
	c	−0.0598	−0.1322
	d	−0.1519	−0.1284
	e	0.0207	0.0255
	f	0.0156	0.0114
	g	−0.0036	−0.0030
Prefer no change	a	63.8114	63.9389
	b	−0.1816	−0.1673
	c	−0.3334	−0.3195
	d	−0.0380	−0.0170
	e	0.0166	0.0236
	f	0.0042	0.0061
	g	−0.0011	−0.0018
Prefer warmer	a	9.8808	11.8711
	b	−1.5918	−1.3512
	c	−0.3210	−0.1849
	d	0.1554	0.1245
	e	0.0733	0.0397
	f	−0.0073	−0.0109
	g	−0.0044	−0.0039

McIntyre vote. To obtain a numerical prediction system for preference/dissatisfaction (PPD*), the McIntyre votes and the ASHRAE votes of a large data base (ASHRAE RP-884 Adaptive Model Project – Data) were correlated so that dissatisfaction could be predicted on the basis of a calculated PMV. This, however, required a good prediction quality for the actual mean ASHRAE vote, in order to get the correct distribution of ASHRAE votes under defined indoor conditions. As the PMV is not a precise predictor of the mean ASHRAE vote for this data set, the PMV was linearly corrected. It should be mentioned explicitly, that this procedure does not aim for a scientific explanation of any differences between PMV and mean ASHRAE vote but was only applied as a necessary step towards a PPD* concept.

Applying the PPD* on the original data and comparing the results with the application of the classical PPD concept shows that improvements of the predictive quality in the region of 10–15% are possible if factors like indoor conditions, outdoor temperature, age, gender, and building type are taken into account. Further improvement of the general predictive quality – which is about 60% – is desirable and might be achieved by looking at differences between more factors or by taking interdependencies between the levels of the factors into account. Apart from the development of a new prediction system for dissatisfaction and the correlated improvement of the predictive quality, the analysis of the mean Preference vote separated by ASHRAE categories opens a different view on thermal environments and their interpretation than the calculation of the mean ASHRAE votes alone.

The model described in this paper is intended to be a theoretical model. It is to highlight a more precise way to determine dissatisfaction with the thermal environment. As the predictive system is applied to the source data which was used to develop the system, the demonstrated quantitative improvement is not sufficient evidence for the supremacy of the PPD* over the PPD. Therefore, the application on an independent data set is necessary.

In thermal building simulations the prediction of user behavior is a key issue, especially for the simulation of NV buildings. Predicting the preference of conditions different from those present is a first step to simulate the interaction between a user and the building. A paper in preparation will propose a psychological model for the user-building-interaction in which the preference and its degree will play

Table 14. Coefficients for PMV to MCI – age

		Age interval									
		14.45	17.00	21.00	25.00	28.50	32.50	35.75	41.25	47.50	62.50
Prefer cooler	a	39.3961	43.0593	27.4669	20.8785	24.2438	22.5521	23.7054	22.3165	15.6647	22.4569
	b	0.6189	0.6535	1.1491	1.0879	1.2456	1.2072	1.1643	1.2428	1.4742	1.1591
	c	−0.0099	−0.0862	−0.2015	−0.1325	−0.2213	−0.1990	−0.2195	−0.1761	−0.1182	−0.0983
	d	−0.0857	−0.0722	−0.1281	−0.0787	−0.1223	−0.1179	−0.0741	−0.1447	−0.2685	−0.1493
	e	−0.0102	0.0077	0.0333	0.0140	0.0339	0.0318	0.0271	0.0407	0.0642	0.0246
	f	0.0132	0.0119	0.0124	0.0083	0.0101	0.0107	−0.0002	0.0067	0.0175	0.0144
	g	−0.0018	−0.0027	−0.0036	−0.0021	−0.0031	−0.0032	−0.0006	−0.0024	−0.0053	−0.0035
Prefer no change	a	46.1532	52.5798	61.0310	64.6628	62.9086	66.0753	64.3214	66.3815	72.7947	71.5600
	b	−0.4134	−0.4137	−0.2473	0.0119	−0.0974	−0.1156	−0.1403	−0.1524	−0.0743	−0.2268
	c	−0.2237	−0.2646	−0.4102	−0.3171	−0.3645	−0.3882	−0.3572	−0.3560	−0.3542	−0.3204
	d	0.0442	0.0189	0.0178	0.0076	−0.0316	0.0037	−0.0288	−0.0287	−0.0025	−0.0085
	e	0.0477	0.0187	0.0319	0.0074	0.0166	0.0373	0.0261	0.0165	0.0188	0.0174
	f	0.0035	−0.0001	−0.0002	−0.0046	−0.0003	0.0004	0.0092	0.0065	0.0012	−0.0005
	g	−0.0041	−0.0019	−0.0043	−0.0008	−0.0014	−0.0055	−0.0017	−0.0006	−0.0011	−0.0036
Prefer warmer	a	14.3949	4.0750	11.6467	14.6502	13.4442	11.6704	12.2771	11.3471	11.5397	6.0536
	b	−0.5197	−1.6212	−1.5355	−1.3329	−1.4856	−1.7664	−1.5074	−1.6082	−1.6033	−1.9087
	c	−0.1852	−0.0283	−0.2916	−0.1427	−0.2854	−0.5175	−0.3057	−0.3998	−0.1570	−0.4930
	d	−0.0767	0.1680	0.0561	0.1265	0.1364	0.0134	0.0755	0.0505	0.2719	−0.0431
	e	0.0297	0.0048	0.0302	0.0250	0.0526	0.0500	0.0396	0.0463	0.0757	−0.0115
	f	0.0035	−0.0334	0.0004	−0.0099	−0.0079	0.0084	−0.0014	0.0029	−0.0161	−0.0170
	g	−0.0023	−0.0076	−0.0009	−0.0026	−0.0035	−0.0002	−0.0017	−0.0012	−0.0056	−0.0040

Table 15. Coefficients for PMV to MCI – PMV*

		PMV* interval						
		−1.350	−0.525	−0.275	−0.115	0.085	0.400	1.125
Prefer cooler	a	16.2945	19.9132	18.1992	22.8108	24.6353	34.4865	37.9613
	b	1.3388	1.1035	1.1333	1.0458	0.9896	0.7904	0.7910
	c	−0.2229	−0.0408	0.0294	−0.0561	−0.0794	−0.0329	−0.0434
	d	−0.1091	−0.1641	−0.1995	−0.1557	−0.1259	−0.1069	−0.1312
	e	0.0340	0.0249	0.0243	0.0197	0.0227	−0.0010	0.0133
	f	0.0075	0.0149	0.0170	0.0180	0.0111	0.0187	0.0161
	g	−0.0026	−0.0036	−0.0038	−0.0041	−0.0028	−0.0036	−0.0035
Prefer no change	a	66.9823	69.5224	71.2733	68.0272	65.8811	56.7784	50.7104
	b	−0.0221	−0.0893	−0.0774	−0.1423	−0.1630	−0.2941	−0.2599
	c	−0.2833	−0.2908	−0.3050	−0.2940	−0.2977	−0.2884	−0.4160
	d	−0.0203	−0.0437	−0.0341	−0.0087	−0.0159	−0.0359	−0.0210
	e	0.0088	0.0178	0.0129	0.0180	0.0280	0.0138	0.0304
	f	0.0024	0.0069	0.0054	0.0027	0.0031	0.0039	0.0037
	g	−0.0005	−0.0019	−0.0010	−0.0015	−0.0031	−0.0010	−0.0004
Prefer warmer	a	16.4416	10.5461	10.7787	9.0768	9.7869	8.4869	11.2542
	b	−1.2070	−1.4358	−1.4575	−1.6330	−1.4395	−1.2926	−1.5555
	c	−0.1149	−0.1409	−0.1993	−0.3425	−0.2340	−0.1918	−0.3362
	d	0.1654	0.2381	0.1830	0.0981	0.1294	0.1036	0.1117
	e	0.0394	0.0676	0.0589	0.0576	0.0453	0.0425	0.0543
	f	−0.0149	−0.0222	−0.0150	−0.0017	−0.0146	−0.0116	−0.0049
	g	−0.0044	−0.0073	−0.0054	−0.0027	−0.0051	−0.0046	−0.0030

Table 16. Coefficients for PMV to MCI – outdoor temperature

		Outside temperature interval							
		−13.5	4.5	13.0	18.0	23.0	26.0	28.5	32.5
Prefer cooler	a	11.8540	10.6315	13.7312	18.1268	28.6331	29.0937	37.1827	40.8583
	b	1.7403	2.0657	1.4987	1.2863	1.0574	0.9499	0.7565	0.6847
	c	−0.5018	−0.8847	−0.3177	−0.1992	−0.1330	−0.0057	−0.0886	−0.0692
	d	0.0009	0.1643	−0.0541	−0.1019	−0.1406	−0.1894	−0.0718	−0.0718
	e	0.0422	0.0485	0.0347	0.0276	0.0248	0.0196	0.0091	0.0097
	f	−0.0111	−0.0313	−0.0034	0.0083	0.0137	0.0223	0.0065	0.0069
	g	0.0008	0.0044	−0.0004	−0.0026	−0.0033	−0.0048	−0.0013	−0.0015
Prefer no change	a	73.8062	74.9980	67.1155	67.7851	61.1566	63.0924	58.2723	54.3371
	b	0.0195	0.0642	0.0421	−0.0801	−0.2573	−0.2779	−0.3675	−0.4004
	c	−0.3197	−0.3501	−0.3015	−0.2803	−0.3397	−0.3476	−0.3207	−0.2948
	d	−0.0191	−0.0020	−0.0002	−0.0080	−0.0206	−0.0156	−0.0247	−0.0238
	e	0.0035	0.0015	−0.0029	0.0113	0.0230	0.0283	0.0317	0.0207
	f	0.0054	0.0038	−0.0001	−0.0038	0.0047	0.0050	0.0083	0.0035
	g	−0.0008	−0.0005	0.0009	−0.0015	−0.0009	−0.0016	−0.0022	−0.0024
Prefer warmer	a	14.4392	14.3597	19.1812	13.9474	9.5759	7.7420	4.9331	5.0043
	b	−1.3905	−1.6766	−1.2335	−1.3590	−1.5835	−1.4908	−1.4983	−1.4161
	c	−0.1139	−0.3916	−0.2419	−0.2992	−0.2167	−0.1838	0.0353	−0.0991
	d	0.1799	0.0854	0.0502	0.0684	0.2464	0.1775	0.2787	0.2012
	e	0.0381	0.0499	0.0219	0.0368	0.0895	0.0598	0.0535	0.0616
	f	−0.0143	0.0018	−0.0012	−0.0026	−0.0130	−0.0162	−0.0327	−0.0250
	g	−0.0040	−0.0012	−0.0009	−0.0019	−0.0060	−0.0060	−0.0092	−0.0085

a major role. Surely, the sole preference of a change of conditions does not make a user necessarily act. Therefore, in our institution, we are aiming to develop a concept of action (PPA, Predicted Percentage Activated) that can be used in thermal building simulations.

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