MASTER

Adaptive thermal comfort in primary school classrooms
creating and validating PMV based comfort charts

ter Mors, S.

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Author
/ Sander ter Mors
/ *Student ID 0575261*

Advisors
/ prof. dr. ir. Jan Hensen
/ dr. ir. Marcel Loomans
/ ir. Atze Boerstra

Jan Hensen

Eindhoven University of Technology
/ Faculty of Architecture, Building and Planning
/ Unit Building Physics and Systems
/ Master of Science Building Services

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This is the final report for the graduation work of Sander ter Mors. This research was done as a graduation project for the Master program Building Services at Eindhoven University of Technology.

The report consists of a paper on the research which was performed, and some related appendices. The paper gives a brief description of the background of the subject, the method used in the research, and the results/discussion with conclusions. The appendices offer extra information on the research and graduation process.

Appendix 1 (Dutch) contains the questionnaires which were used in the research, and this appendix could be added to the paper. The other appendices are sorted in a similar way to the paper, so first the introduction and literature review are treated, followed by the method and finally the results/discussion.

This research would not have been possible without the help and advice of various persons. First, I would like to thank my supervisors, Jan Hensen, Marcel Loomans and Atze Boerstra, for their support and valuable input, both on the subject and the process. They also helped me contact Michael Humphreys who offered me brief but valuable input from his own research and other relevant references. Wout van Bommel provided me with much needed support with the measurements, which on their own could not have taken place without the co-operation of the primary schools, their teachers and the children from the classrooms. I would also like to thank all my fellow students, with whom it was a great pleasure to work during the past years I spent at the university. Finally I would like to thank my parents and the rest of the family, who encouraged and supported me throughout this study.

Sander ter Mors

Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts

Sander ter Mors
Eindhoven University of Technology, Eindhoven, Netherlands

1. Abstract

In this research the thermal comfort and thermal comfort parameters for non-office conditions have been investigated, specifically for children in primary school classrooms. Actual thermal sensation and clothing insulation of children (age 9-11) in non-air-conditioned classrooms in three different schools in the Netherlands have been obtained. Results are available for a total of 24 days, covering winter, spring and summer conditions (year 2010). Questionnaires have been applied to obtain the actual thermal sensation and clothing insulation in the morning and afternoon of regular school days. In this period physical parameters (temperature, relative humidity, etc.) were recorded as well in order to derive the PMV.

The results show that children adapt clothing during the year from mean values around 0.9 clo in winter to 0.3 clo in summer, with the largest changes occurring in the mid-season. There is a small difference in clothing adaptation between male and female children, with the females showing more adaptation.

Comparison of the actual mean vote with the calculated PMV, based on the measured data, indicates a clear difference. The conclusion is that the PMV model does not predict the thermal sensation of these children accurately; it underestimates the mean thermal sensation up to 1.5 scale point. This can be explained by the fact that the children's heat balance with the thermal environment is different from adult's, on which PMV is based. This difference lies mainly in the influence of metabolic rate on thermal sensation.

When the actual thermal sensation votes are compared to comfort predictions based on adaptive temperature limits it shows that children prefer lower temperatures than predicted by these methods.

Keywords: Predicted Mean Vote, Clothing Insulation, Assessment Methods

2. Introduction

The Adaptive Temperature Limits (ATL) [1] method which is used in the Netherlands was developed for naturally ventilated office buildings. It shows the required operative temperatures as function of a weighted running mean of the exterior temperature; this is a very easy-to-understand representation of thermal comfort criteria. Another method to predict thermal comfort is Fanger's Predicted Mean Vote (PMV) [2]. Earlier research by van der Linden et al [3] indicated that this method, with correct input, can lead to similar predictions for thermal comfort in a moderate climate like the Netherlands. The advantage of this method is that its input can be adjusted to the specific situation to be evaluated, so the range of buildings it can be applied to is broader.

This research goes into thermal comfort evaluation methods for primary school classrooms in the Netherlands, to see whether the PMV method can be used to improve accuracy of predictions. Specific attention was given to the clothing insulation for children, and adaptation of clothing during the year.

It is important to keep in mind the difference between thermal comfort, thermal sensation and thermal preference. Thermal comfort is defined by ASHRAE [4] as 'that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation'. The subjective evaluation of thermal comfort is influenced by the thermal environment and personal factors influencing the heat transfer with this environment, but also by psychological factors influencing the condition of mind directly. All these factors in thermal comfort can be altered by behavioural, physiological or psychological adaptation.

2.1. PMV method

Many thermal comfort criteria and predictions are based on the PMV as introduced by Fanger [2] and presented in ISO 7730:2005 [5]. This comfort equation can be used to calculate the PMV, the predicted average thermal sensation for a large group of persons, on the seven point scale thermal sensation scale which is shown in Table 1. This predicted thermal sensation can be transferred to the predicted thermal comfort in the form of Predicted Percentage Dissatisfied (PPD), which is the predicted percentage of people in a large group that will be dissatisfied at a PMV value. A PMV of 0 does not mean every individual has thermal neutrality, so even then the PPD is not zero.

Fanger's comfort equation is derived from extensive climate chamber research. The responses of over a thousand European and American subjects to the thermal conditions in a well-controlled environment were used to expand this equation into the PMV model. This equation and the PMV model are intended for use in the design of HVAC systems.

Table 1: Seven-point thermal sensation scale [5]

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

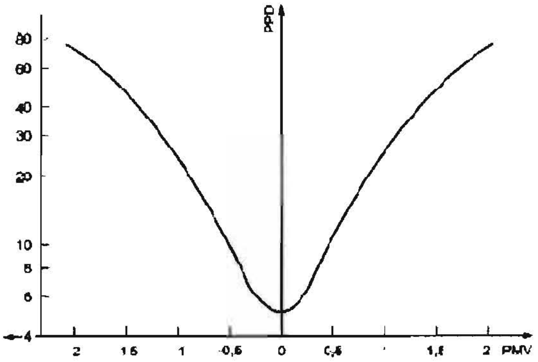


Figure 1: Predicted percentage dissatisfied as a function of predicted mean vote [5]

The calculation for the PMV takes into account the thermo physiological properties of humans and their thermal balance with the environment. On a personal level this includes the activity level and clothing insulation. The thermal environment is determined by the variables air temperature, mean radiant temperature, relative humidity, and air velocity. Physiological variation and psychological effects are not taken into account in the PMV model. In [6] it is shown that for HVAC buildings this method can accurately predict comfort temperatures, but for free-running buildings the thermal sensation is underestimated in winter and overestimated in summer. Psychological adaptation is given as the most likely reason for this divergence.

ISO 7730 [5] gives validity intervals for the PMV variables, and when one or more of the variables are outside this range the results from the model are no longer considered reliable. These validity intervals are discussed by Humphreys and Nicol [7] who conclude that the ranges for valid use of PMV are much narrower. They also conclude that the resulting bias in PMV outcome can be very misleading when assessing thermal comfort among people in everyday conditions, and state that it could be useful to reconsider the relations between metabolic rate, skin temperature and sweat production for comfortable conditions.

The relation between PMV and PPD is also subject to discussion. In [8], results from various climate chamber and field researches are shown to vary (strongly) from Fanger's PMV/PPD relation. Corgnati et al [9] found a trend for thermal preference from slightly warm environments in the winter period to neutral environments in the temperate season.

The clothing insulation and metabolic heat production can be estimated, but practical methods to do this are not accurate and cause a large part of the uncertainty in the final thermal sensation prediction. Improving the methods to determine clothing insulation and metabolism can improve accuracy and quality of PMV based predictions [8]. Clothing insulation determination methods based on tables stating insulating values for various garments can vary 20% in results [10], also influencing the PMV outcome.

Havenith et al [11] investigated methods to determine metabolism and clothing insulation. One of their conclusions is that posture and air speed can cause a reduction of clothing vapour resistance, and the impact this has on comfort limits in terms of skin wettedness cannot be neglected. Furthermore they conclude that to improve metabolic rate estimation for activities below 2 met by using ISO 8996 [12] more data and detail is needed, and that the current methods described in ISO 8996 are not sufficiently accurate to estimate PMV within 0.3 scale points.

Besides all critique on the PMV model and its performance in predicting thermal comfort, many times no alternatives for field use are given. For some specific regions or application ranges, [7] and [13] do offer (methods to implement) empirical improvements to the PMV model. In [8] a variety of PMV model adjustment and improvement studies are described. In [14], Fanger and Toftum introduce the expectancy factor 'e' as addition to the PMV model, specifically for use in non-air-conditioned buildings in warm climates. In this situation the expectancy of indoor climate is low, so higher temperatures are accepted and not always considered uncomfortable. The value of the expectancy factor will always be in the range 0.5 – 1.0 and is determined by location and frequency of warm periods. The calculated PMV is multiplied by the expectancy factor, which results in the new PMV. Since in the Netherlands warm periods are not common the expectancy factor will be 0.9-1.0. A value of 1.0 would mean that the calculated PMV will not change, so the expectancy factor has little or no influence in the Netherlands.

2.1.1. Thermal Comfort for Children

In the original thermal comfort research by Fanger, there were no children included in the climate chamber tests. This lead Fanger to state that more research would be required to test if the comfort equation could be applied to (young) children.[2] The relations between metabolic rate, skin temperature, sweat production and thermal sensation or thermal comfort which are the base of the PMV model might not be the same for children.

According to Humphreys [15], children seem to be a little less sensitive to temperature change than adults, and there is also a larger variation among the responses of children. The cause that is given for these observations is the higher normal activity level of children, and the fact that there is a large variety in the activity level during education. The children that participated in this research did not change their clothing during the day. The average clothing value changed only on the longer term, but the room temperature and mean thermal sensation did change during the day.

Besides the possible difference in the relation between metabolic rate and thermal sensation, the metabolic rate itself is also different for children than adults. This is shown by Havenith [16], who investigated the metabolic rate and clothing insulation for various classroom types and age groups. From this research it can be concluded that the metabolism for 9-11 year old children varies from 52 to 64 W/m^2 for various sedentary classroom activities. For adults this would be higher, around 70 – 100 W/m^2 when estimated by ISO 8996:2004 as 'clerical work' [12]. ISO 7730:2005 [5] estimates sedentary office activity metabolism at 1.2 met (1 met = 58.2 W/m^2), which is equal to the ISO 8890 estimation lower limit of 70 W/m^2.

A different approach to determine the metabolic heat production for children is presented by Parsons [17]. Here he states that, as a first approximation, the data from ISO 8996:1990 (this version of the standard has been replaced by [12]) may be used with appropriate correction for reduced mass and surface areas of the body. It is however not specified how this correction should be applied.

2.2. *Other assessment methods for thermal comfort*

NEN-EN 15251 [18] and ASHRAE Standard 55-2004 [4] are the most widely used adaptive assessment charts for thermal comfort. These adaptive methods do not base their predictions on the heat balance but instead use field research data for thermal sensation, preference and acceptance. Even though the two seem similar, there are four important differences which are discussed in detail by Nicol and Humphreys [19]: They are derived from different databases; the building type they apply to is not the same; the method used to determine neutral temperature is different; and the exterior temperature variable used is different.

ISSO 74 [1] is a Dutch adaptive guideline which introduces another building classification and exterior temperature variable. These limits are based on and extended from [6], on which the ASHRAE Standard 55-2004 is also based. Since (practically) all buildings which are free-running in summer do have active heating for colder seasons, ISSO 74 combines the adaptive limits for the free-running season with HVAC limits for the heating season. For external climates below 10-12°C θe,ref (4 day weighted running mean temperature) the limits for all building types are equal, only the upper temperature limits for higher temperatures differs. ISSO 89 [20] is a guideline for the indoor climate in schools, and the thermal comfort limits shown here are a simplified version of the adaptive limits to make this guideline better understandable for primary school boards.

The various exterior temperature definitions used in the comfort standards mentioned are shown and explained in Table 2.

Table 2: Variables to define external climate as used in various standards

Standard	Exterior Temperature variable	Definition
ASHRAE 55-1992	ET*	Mean daily outdoor effective temperature
ASHRAE 55-2004	$t_{a(out)}$	Monthly mean of daily min/max mean
NEN-EN 15251	θ_{rm}	Weighted running mean of daily mean, excluding current day
ISSO 74	$\theta_{e,ref}$	4 day weighted running mean of daily min/max mean, including current day
ISSO 89	θ_{bu}	Current external temperature

2.3. *Main research aims*

Earlier research [3] has shown that the PMV model, using correct input, can explain the adaptive limits from ISSO 74[1]. The main aim of this research is to investigate if the Fanger-method can be used to develop 'simple' comfort charts, similar to the Adaptive Temperature Limits, but for non-office buildings and specifically a primary school classroom.

To achieve this all variables in the PMV method will be determined for this situation. The variables can be influenced by exterior climate, meaning the value will change during the year. Another possibility is change based on interior or local climate, changing the value during the day. Users can also adapt the personal factors which influence the heat balance in order to maintain personal thermal comfort. This adaptation can be physiological, psychological or behavioural. The focus in this project will be on behavioural adaptation, and specifically on the variable clothing insulation. This will show how children adapt their clothing with changing exterior climate during the year.

3. Methods

A field research was conducted in non-air-conditioned classrooms in three different schools in the Netherlands. In order to derive the PMV for the children (age 9-11) in these classrooms questionnaires were applied to obtain the activity level and clothing garments worn in the morning and afternoon of regular school days, and the physical parameters which influence the thermal sensation were recorded as well. This was done for a total of 24 days in three sessions, covering winter, spring and summer conditions (year 2010). Besides the data needed to determine the PMV the actual thermal sensation and satisfaction were included in the questionnaires as well to obtain the subjective evaluation of thermal comfort. Thermal satisfaction was only included in the mid-season and summer measurements.

Clothing values were calculated using garment insulation values from ISO 7730 [5]. The aim was to keep the questionnaire easy-to-understand and concise. To do this, clothing which was not expected to be worn was excluded from the list. Also, for t-shirts vests and dresses three variants were included; sleeveless, short sleeve and longsleeve. When the clothing ensemble specified was not realistic, the data was disregarded. When minor clothing garments were missing (shoes, socks or underwear) this value was estimated. Data for the teachers was also recorded, but not used in the analysis. For the insulating value of the chair a value of 0.01 clo (1 clo = 0.155 m^2K/W) was used since open wooden chairs were used in the classroom.

Metabolic rate was determined with classification according to activity, using ISO 7730 [5] instead of ISO 8996 [12] since the latter method would classify all school activities as 'low metabolic rate' without further distinction. Further distinction was possible by determining the metabolic rate in met, using the categories 'Seated, relaxed' (met=1.0), 'Sedentary activity' (met=1.2) and 'Standing, light activity' (met=1.6). This metabolic rate was corrected for the reduced surface area by multiplying it by 1.7/1.14. The mean body surface area is 1.7 m^2 for adults and 1.14 m^2 for 10 year olds. [21] Reduced mass was not taken into account, external work for classroom activities can be estimated as 0 W. This results in metabolic rate values of 86, 104 or 139 W/m^2. For comparison of resulting thermal sensation predictions, the metabolism will also be changed to 60 W/m^2, estimated based on the data found by Havenith [16].

The three classrooms were located in buildings built in 2002, 1994 and 1964, and all located on the top floor of the building. All had centrally controlled heating by radiators and operable windows. The first school did have mechanical exhaust ventilation, but at a very low volume so operable windows were the main source of ventilation in all seasons. For the second school this was the case in winter and mid-season, but in summer the mechanical exhaust volume was set higher, windows were kept closed and a local cooling unit was placed in the classroom. Still the indoor climate showed a free-running temperature trend, so the influence of this cooling was minimal. The third school had only operable windows for ventilation.

In each classroom the physical parameters were recorded on a single location. The air temperature, globe temperature, air humidity and air velocity were logged at an interval of 6 minutes at heights between 0.5 and 1.0 meter, since it was not practically possible to install all sensors at the ISO 7726:1998 [22] prescribed height of 0.6 meter.

Clothing insulation and metabolic rate were determined with questionnaires, which inevitably leads to an uncertainty in the results. This method was chosen to minimize the impact on the children's classroom activities. Since the aim of the research is exploratory and not much is known about clothing insulation at changing exterior temperatures for children, this method will result in new information.

4. Results

4.1. Climate indoor and outdoor during measurement periods

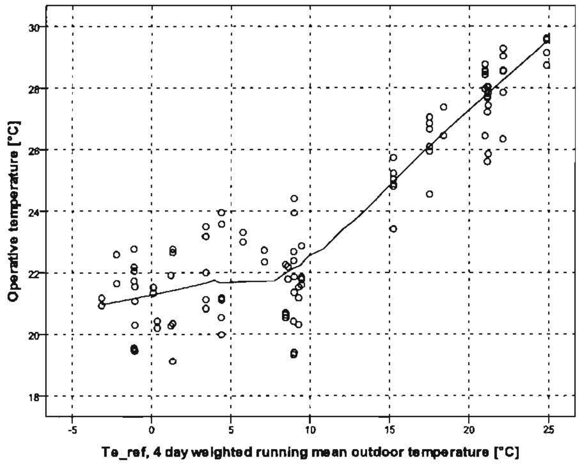


Figure 2: Operative temperature and exterior climate in the form of θe,ref

The figure shows that indoor operative temperature follows the exterior running mean temperature. During winter and mid-season the interior temperature is not influenced much, but when the exterior temperature rises the indoor temperature follows this trend, rising about 0.5 K for each 1 K (4 day weighted mean) increase outside. The exterior temperatures during the seasons were within normal ranges, but the summer measurements took place during the warmest days of the year. The trendline shown is a Locally weighted scatterplot smoothing (LOESS) curve (Epanechnikov kernel, 50% fit).

4.2. *Clothing insulation results*

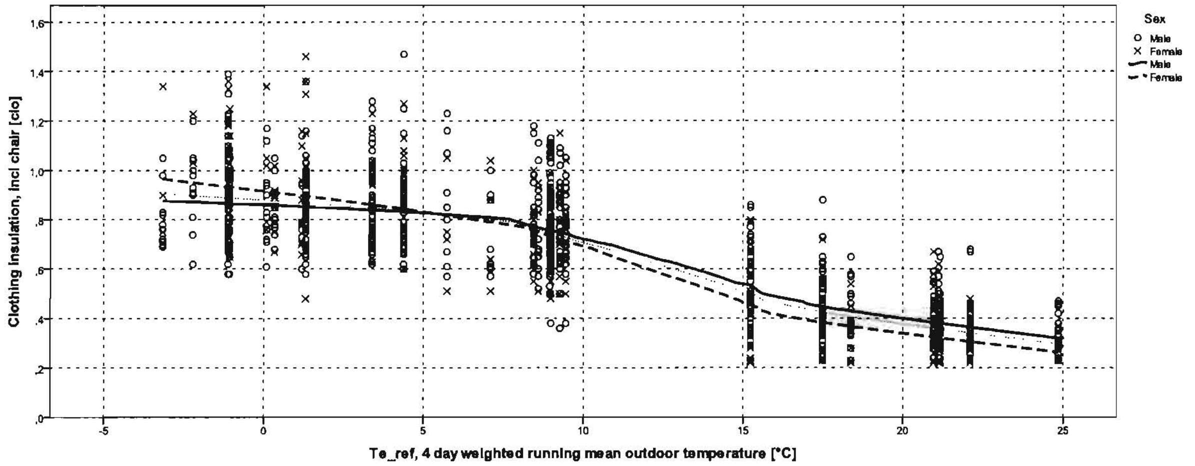


Figure 3: Individual clothing insulation for male and female children against θe,ref

As is to be expected, the clothing insulation shows a negative trend with increasing exterior temperatures. The decrease in clo is not constant during the year; the largest changes happen during the mid-season.

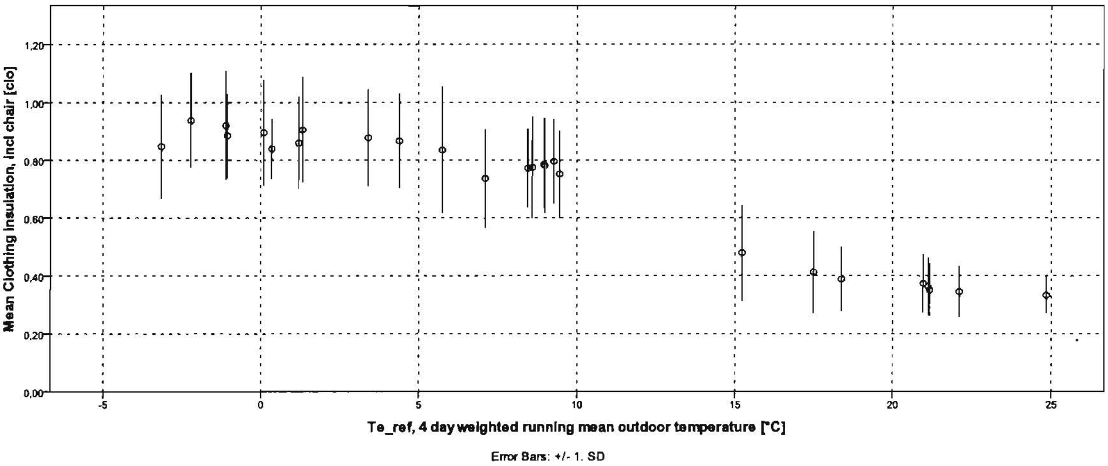
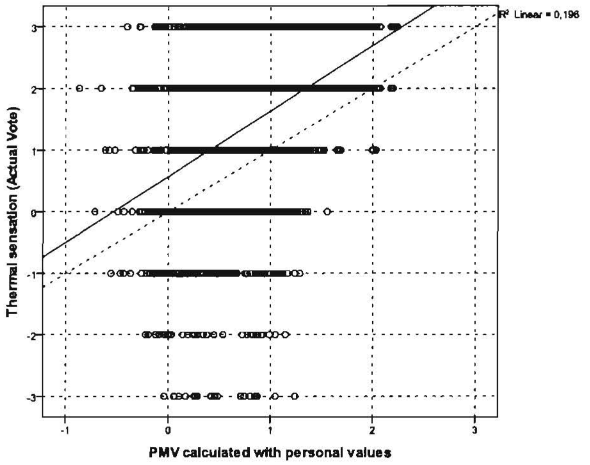


Figure 4: Mean clothing insulation and standard deviations against θe,ref

The standard deviation for the mean clothing insulation is lower in summer, similar to the results presented by Corgnati et al.[9]

4.3. *PMV predictions*



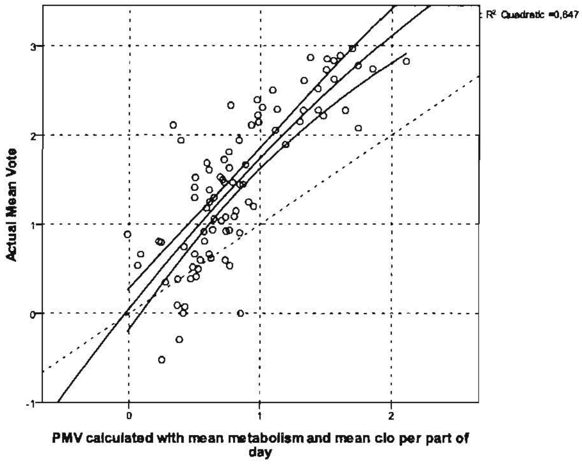


Figure 5: Thermal sensation and individual PMV

Figure 6: Actual mean vote and PMV

Figure 5 shows the actual thermal sensation against the PMV calculated with the personal values (met*1.7/1.14 and clothing insulation from questionnaires) and mean environmental values for that part of day. The second figure shows Actual Mean Vote for the part of day against PMV calculated with actual mean personal and environmental values for that part of day. In both figures a trendline is shown with corresponding R^2 value. The dotted line in both figures shows Actual=Predicted, so ideally all values would be on this line. The reality is that actual (mean) sensations are mostly higher than PMV.

5. Discussion

5.1. Method

What should be taken into account when evaluating the results is that they are based on a relative small sample of three classrooms (79 children) and conclusions therefore should be assessed as preliminary.

The average vote during the summer period was above +2 for two out of three schools. Since this is far away from neutral thermal sensation, results might be unreliable in these cases. Even so, the PMV method's reliability ranges stated in ISO 7730 [5] are not exceeded except for one predicted mean vote above +2, and a few short moments where the temperature was above 30°C. For the individual PMV calculations more predictions were above +2.

The measured air speeds were very low; the mean was around 0.05 m/s in winter and showed a linear rising trend to 0.08 in summer, even though windows were opened. It is unclear whether this is caused by low outdoor air speeds, and if these air speeds occur in all schools in the Netherlands. Higher air speeds could offset high indoor air temperatures and thereby lower the mean thermal sensation. The relative air humidity was also quite low with values from 20% to 50%, but still mostly within comfort limits.

Effects of air speed and body movement on the vapour resistance and thermal comfort [11] have been neglected, since the influence of skin wettedness on the thermal sensation for children is unknown.

Determining clothing insulation of garments can lead to variations of 20% depending on the source used [10], so the values found might be different when a different source is used. The simplifications and assumptions concerning the questionnaires themselves lead to an uncertainty of about 0.1 clo, depending on the season. Also since the metabolism tables from ISSO 8996 [12] are used the PMV predictions might not be accurate within 0.3 scale points [11].

5.2. Clothing insulation during the year

There is only a small difference between male and female's clothing insulation, similar to results from a study by Humphreys [15] where clothing for 7-9 year olds in a classroom was studied. For (mean) clothing insulation for adults in office buildings, de Carli et al [23] also showed a small difference between male and female, whereas Fishman and Pimbert [24] found a large difference. The mean clothing insulation in winter is about 0.9 clo, which is comparable to values recorded by the previously mentioned sources and de Dear et al [6]. This value drops to about 0.3 clo in summer, which is slightly lower than the minimum values in the previously mentioned sources, but significantly lower than the mean in [6] and mean for males from [24] at comparable exterior temperatures.

The local regression curve from Figure 3 can be described with three linear functions, which roughly match the winter, mid-season and summer seasons. These functions are shown in Table 3. Outside of this range for external temperatures the mean clothing insulation is unknown, but this range almost fully captures the Dutch climate.

Table 3: Multi-period linear function for children's mean clothing insulation

θe,ref [°C] range	Linear relation
-3 < θe,ref < 8;	$Mean\ clo = 0.9 - 0.1 * \frac{\theta e,ref - -3}{11};$
8 < θe,ref < 16;	$Mean\ clo = 0.8 - 0.34 * \frac{\theta e,ref - 8}{8};$
16< θe,ref < 25;	$Mean\ clo = 0.46 - 0.16 * \frac{\theta e,ref - 16}{9};$

As mentioned earlier, the clothing insulation is similar to office-working adult's average clothing insulation in winter. During the summer period the children mostly wore shorts, slippers and a t-shirt for a total clothing insulation around 0.25-0.30 clo, whereas in office buildings this clothing ensemble is often not accepted. This means that the average clothing insulation for children can assume slightly lower values in summer than that of adults in an average office environment.

Linear regressions have been done for both the mean and individual clothing insulation, for external temperatures Tmin (daily minimum temperature), Tmean (mean of daily minimum and maximum), θe,ref and θrm. It can be seen that the R^2 value for both clo values is highest for the linear regression with θe,ref, but the difference with Tmean and θrm is negligible and with Tmin is small. Assuming that Tmin is equal to T6am, this is contrary to de Carli et al [23]. Here, the difference in correlation coefficients for NV buildings was highest for T6am, also with a small difference. For HVAC buildings all differences were negligible.

Table 4: Linear regression functions and R^2 values

	Tmin	Tmean	$\theta_{e,ref}$	θ_{rm}
Mean clo	0.816-0.029*Tmin	0.930-0.024*Tmean	0.927-0.025*$\theta_{e,ref}$	0.934-0.028*θ_{rm}
	R^2=0.848	R^2=0.910	R^2=0.919	R^2=0.913
Individual clo	0.827-0.032*Tmin	0.942-0.025*Tmean	0.936-0.026*$\theta_{e,ref}$	0.937-0.029*θ_{rm}
	R^2=0.627	R^2=0.670	R^2=0.675	R^2=0.671

5.3. PMV predictions – Actual sensation

Analytical PMV, calculated with actual (mean) values for clothing insulation, metabolism and air speed, underestimates the thermal sensation vote. This is remarkable, since most previous research which found an error in PMV predictions found an overestimation of thermal sensation. An expectancy factor of 1 (no influence) was used; if this is changed it would only make the underestimation larger.

The largest errors occurred during the mid-season, but on average the underestimation in summer was larger. These mid-season errors are exceptional cases, so the higher mean underestimation during summer is where the actual largest unreliability in the PMV prediction lies. During the summer, at $\theta_{e,ref}$ of 15 to 25°C, the error lies between 0.5 and 1.5 scale points, with a mean of about 1. The scale of this error shows that the PMV method, using a surface-area corrected metabolic rate, does not result in valid predictions of the thermal sensation of children.

The mean metabolic rate determined from the questionnaires was 1.26 met. This value was quite constant for all schools and seasons, and did not show dependence on any of the other measured variables. When this value is multiplied by $58.2 * \frac{1.7}{1.14}$ to take the reduced surface area of children in account this results in 109 W/m^2. With this value for metabolism in the PMV function, Figure 5 and Figure 6 were created. If the actual W/m^2 are used, estimated at 60 Wm^2 based on [16], the underestimation of thermal sensation by the PMV method is even larger, as is shown in Figure 7. The physiological basis for PMV is that of adults, for children the relation between all personal and environmental values and thermal sensation is different. Possibly the metabolism should be included in a different way than using W/m^2 when predicting thermal sensation for children. Even though it might not be accurate physically, basing the metabolic rate for the PMV calculation on the assumption that the same total heat is produced by children and correcting this for reduced body surface area results in thermal sensation predictions which are closer to reality than when actual Watts per m^2 body surface are used.

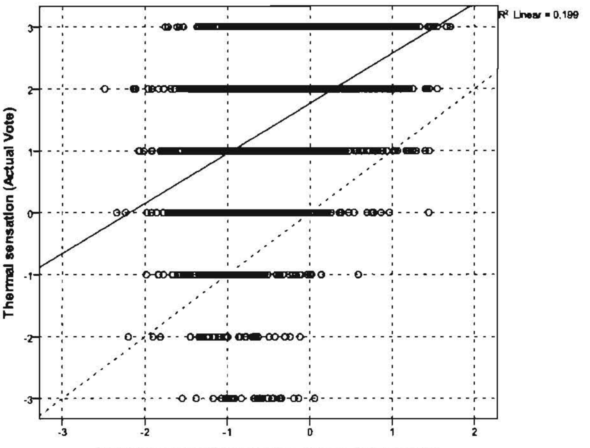


Figure 7: Thermal sensation and individual PMV with actual W/m^2 based on [16]

The temperature ranges for use of PMV stated in ISO 7730 [5] are 10-30°C for air, and 10-40°C for radiant. Humphreys et al [7] showed that discrepancies in PMV are to be expected at operative temperatures above 27°C, but this would still only account for unreliable results for a small part of the current data.

The adaptive PMV method, calculated with the multi-period linear function for clo, a constant metabolic rate of 111 W/m^2, and the linear function for v, gives results similar to analytical PMV. The maximum difference between the analytical and adaptive approach in this research was 0.6, and on average the difference was 0.17 scale points. This comparison is shown in Figure 8. With this reliability range of about 0.5 scale points in mind, this adaptive PMV method could be used to create comfort limits for situations where similar clothing insulation, air speeds and activity levels are to be expected, but this is not useful since the predictions themselves are not accurate.

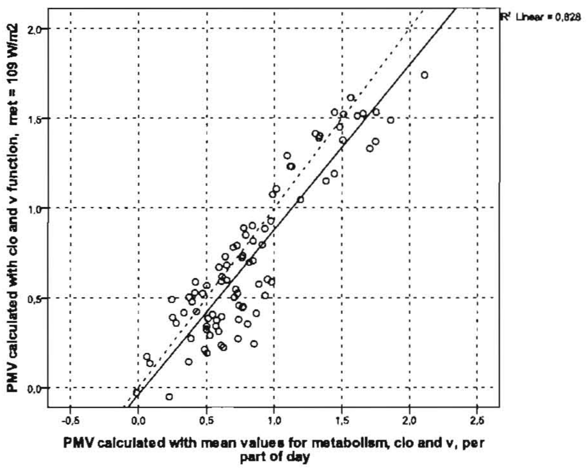


Figure 8: Comparison of analytical PMV and adaptive PMV

5.3.1. PMV predictions – assessment methods

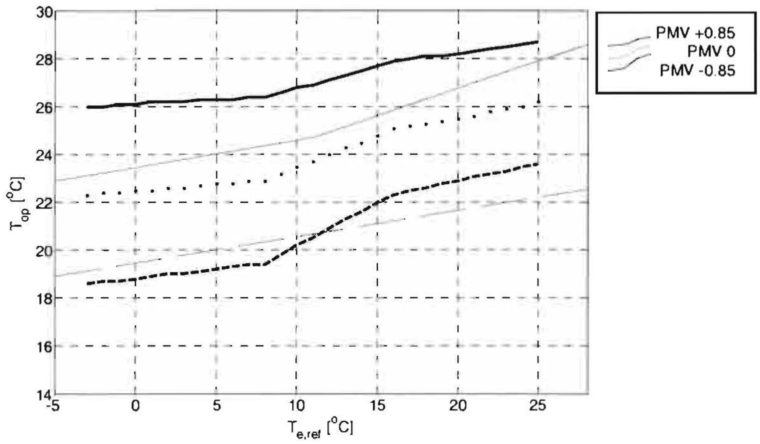


Figure 9: Adaptive PMV based temperature limits at 70 W/m², compared to ATL type Alpha 80% acceptance

When an adult's sedentary activity metabolism of 70 W/m² is used in the calculations, the adaptive PMV based comfort limits are similar to the ATL if the standard PMV/PPD relation is assumed where a PMV of +0.85 gives 20% dissatisfied. If the clothing insulation in summer is slightly higher, which is realistic for adults in an office situation, the limits are even more comparable. The influence of clothing insulation can be seen clearly in the general course of the PMV limits, where the largest changes also happen mid-season. At higher clothing insulation values, the operative temperature has less influence on thermal sensation. Therefore the PMV limits at low external temperatures (and high clothing insulation) are much wider than at high external temperatures (and low clothing insulation).

Table 5 shows the actual percentage and amount of children dissatisfied for each thermal sensation vote and season, with corresponding total amount of children for that thermal sensation. Since the PMV method is only reliable for the range -2 to +2, the two outer categories do not show the standard PPD. These results show that the minimal actual percentage dissatisfied is higher than the PPD, but that the dissatisfaction at warmer thermal sensations is lower. For the cooler thermal sensations there is very few data available. Looking at the mid-season data, it can be concluded that children have a wider range of acceptable thermal sensations.

The percentage dissatisfied is higher for all thermal sensations in summer. During the winter measurements thermal acceptance was not determined. During the summer season, a thermal sensation of +2 corresponds with 58% dissatisfied, where in the mid-season this is only 27%. There is also more dissatisfaction for a vote of +3 in summer. The same trend that was predicted by McIntyre, cited and confirmed by Corgnati et al [9] can be seen in this. They have shown that the thermal preference in winter lies at a thermal sensation vote of about +1, and during the mid-season closer to +0. The explanation for this is that people in a cold climate prefer a slightly warm thermal environment, whereas persons in a hot climate prefer a slightly cool sensation. If comfort limits are created based on PMV this should be taken into account, to ensure an assessment of thermal comfort instead of thermal neutrality.

Table 5: Thermal sensation and acceptance per season

		-3	-2	-1	0	1	2	3	Total
Winter	n	25	31	67	161	235	189	86	794
Mid-season	n	6	4	29	112	135	144	79	509
	n dissatisfied	5	2	5	10	21	39	49	122
	% dissatisfied	83%	50%	17%	9%	16%	27%	62%	24%
Summer	n	0	1	9	51	115	282	405	863
	n dissatisfied	0	1	3	14	29	164	344	555
	% dissatisfied	-	100%	33%	27%	25%	58%	85%	64%
Standard PPD	% dissatisfied	-	75%	25%	5%	25%	75%	-	

5.3.2. *Actual sensation – assessment methods*

Since the PMV assessment is not applicable for children without large-scale research on the thermal heat balance and comfort for children, other assessment methods will have to be investigated. Of the available assessment methods most are not developed for these building types, but their building-type application range will not be discussed here. The question is whether they can be used to accurately assess children's thermal comfort.

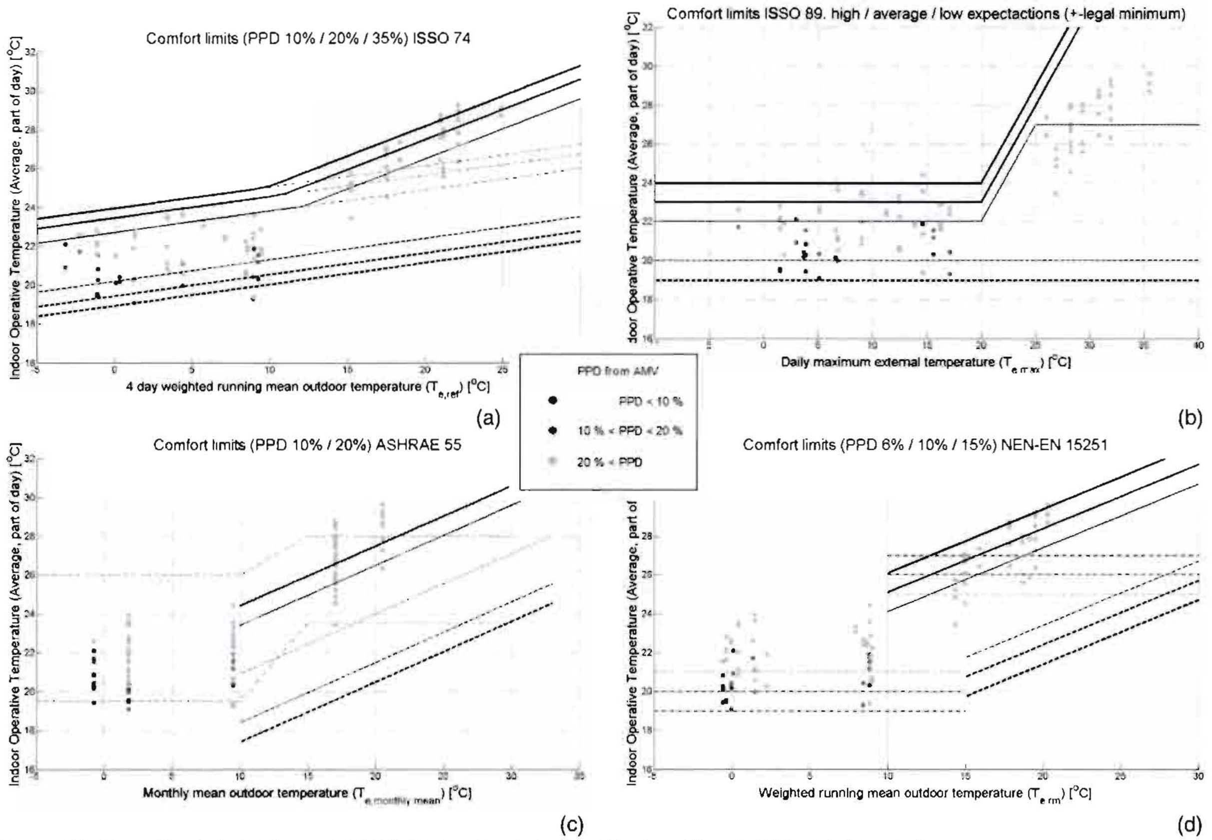


Figure 10: Operative temperatures and adaptive assessment methods, with actual thermal sensation

Most of the measured conditions were within the ISSO 74 [1], ISSO 89 [20] and EN-15251 Annex A2 [18] outer limits, but ASHRAE standard 55 [4] is stricter in this situation. The high temperature limits for categories II and III from ISSO 89 are very tolerant at high external temperatures. EN-15251 Annex A2 used categories which are supposed to be stricter, with only 6 10 or 15% dissatisfied, where ISSO 74 uses 10, 20 and 35% and ASHRAE 55 10 and 20%. In reality these limits are comparable to the ISSO 74 Alpha limits. For the ASHRAE and EN figures indications of the heating season / static limits are shown in gray lines; normally these are not represented in this type of graph so these are not the exact prescribed limits.

Even though nearly all measured situations would fall within the limits, the mean thermal sensations show a very different picture. Only at the lowest external temperatures the mean thermal sensations are near neutral. In ISSO 74 the Bèta limits (gray lines) are stricter for high external temperatures, and using these limits would result in a more accurate prediction of the children's discomfort. Children are free to adapt their clothing or posture, but do not have full personal control of operable windows. These are either controlled by the teacher or by a few children, so not all children have individual control of the windows. This would mean the building needs to be assessed as type Bèta, but this does not seem a feasible limit for a primary school. For the cooler external climate temperatures predicted to be comfortable by this and other limits are actually considered warm. When thermal acceptance is used the results are more comparable to the various adaptive limits since not only a neutral sensation is acceptable, but still a lot of temperatures which are assessed as comfortable by the limits are actually considered unacceptable. Thermal acceptance was only determined in the mid-season and summer, so this data is not shown here.

6. Conclusions

The mean clothing insulation for 9-11 year old children in a primary school classroom can be described by a three-period linear functions of θe,ref. The mean clothing insulation changes most during the mid-season. The difference between male and female is small; the largest difference is about 0.1, this occurs at a θe,ref of -3°C. The mean changes from 0.9 at a θe,ref of -3°C to 0.8 at 8°C, 0.46 at 16°C and 0.3 at 25°C.

From the obtained results for this small group (n=79) it can be concluded that the PMV method underestimates thermal sensation for children, while most previous research which found errors in PMV predictions found that it overestimated thermal sensation. The error is largest in summer, with underestimation ranging from 0.5 to 1.5 scale points at θe,ref of 15 to 25°C. For these results the metabolism was estimated by using adult's data corrected for reduced body surface area. This results in an average of 109 W/m^2 in this research, which is higher than for an adult in sedentary activity (70 W/m^2), but as indicated the resulting PMV is still lower than actual thermal sensation. The metabolism in actual W/m^2, which can be estimated at 60 W/m^2 for 9-11 year old children in sedentary classroom activities based on research by Havenith [16], results in a lower PMV so an even larger underestimation in predictions. This shows that the PMV method can not be applied to children in a classroom situation, and that PMV with surface area-corrected metabolism is better but still does not result in valid predictions of the thermal sensation of these children.

Comfort limits comparable to the ATL could be created from PMV predictions; by predicting clothing insulation, metabolism and air speed based on the field research results, the operative temperature for certain PMV values can be calculated. These limits are, however, not accurate for children since the PMV does not predict actual thermal sensation for this group accurately. For adults the limits are comparable to the ATL, as was also concluded by van der Linden et al [3]. High clothing insulation in winter results in a wider range of predicted comfortable operative temperatures compared to the adaptive limits and summer period. These PMV based limits need to be improved by including seasonal influences on thermal preference.

The actual thermal sensation does not support use of current adaptive thermal comfort assessment methods. Similar to the PMV predictions, these adaptive limits underestimate the thermal sensation and predict higher comfortable temperatures than those actually indicated by the children. This means that the currently applied assessment methods for primary schools are not correct, and complying with these demands does not necessarily lead to a comfortable situation for children.

7. Further research

More research is needed on the subject of thermal comfort of children, since the assessment methods for adults do not seem applicable. This is the case for assessment by PMV and also for adaptive limits. For PMV the role of metabolism in the heat balance and comfort of children needs evaluation, since the physiological basis of the method is that of adults and the relations between metabolism, surface temperature, sweating etc. and thermal sensation and comfort are different for children.

If PMV based comfort limits are to be created, these should take into account the seasonal influences on thermal preference. For this, more research on thermal sensation and thermal preference in various seasons or climates is needed.

8. Acknowledgements

This research would not have been possible without the cooperation of the three schools, and the valuable input of the teachers and children in the classes. Also I would like to thank Michael Humphreys for the helpful email correspondence.

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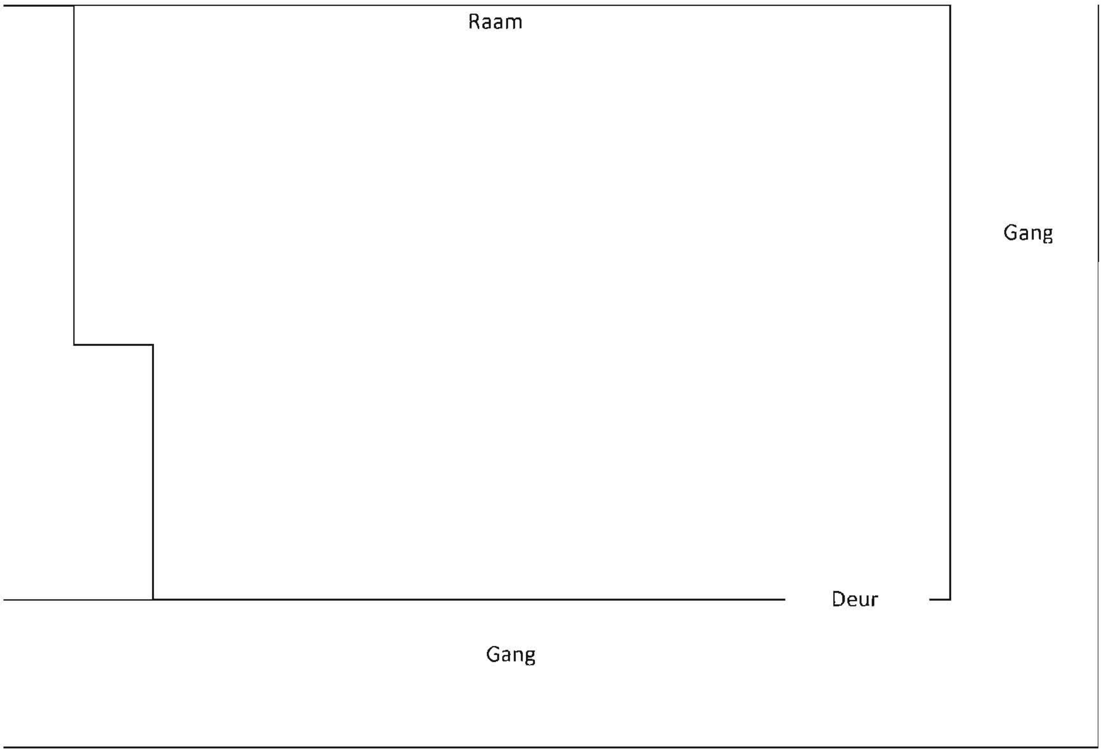
Appendices

A1. Questionnaires

Included on the following pages are the questionnaires which were used for the children and teachers in the classrooms.

Vragenlijst leerling Naam:..

1. Ben je een jongen of meisje
   ☐ Jongen ☐ Meisje
2. Hoe oud ben je?
   ......jaar
3. Geef hieronder aan waar je op dit moment ongeveer in de klas zit.



Ochtend

4. Hoe voel je je op dit moment?

☐	☐	☐	☐	☐	☐	☐
Heet	Warm	Een beetje warm	Niet warm, niet koud	Een beetje koel	Koel	Koud

5. Hoeveel tocht voel je?

☐	☐	☐	☐	☐	☐	☐
Helemaal geen tocht		Een beetje tocht		Last van tocht		Veel last van tocht

6. Wat heb je het afgelopen uur vooral gedaan?
   ☐ Vooral rustig zitten, lezen
   ☐ Vooral zitten, schrijven of knutselen
   ☐ Veel staan of rondlopen
7. Vind je de temperatuur binnen acceptabel?
   ☐ Ja, acceptabel
   ☐ Nee, niet acceptabel

Als je plaats in de klas op de middag anders is dan op de ochtend, of je andere kleding aan hebt, dit graag aangegeven in de plattegrond of vragenlijst. Wel erbij zetten wat voor de middag ingevuld is.

Ruimte voor opmerkingen: ....

....

Kleding

8. Geef hieronder aan welke kledingstukken je aan hebt.

Ondergoed

- ☐ Onderbroek (evt. incl. BH)
- ☐ Boxershort
- ☐ Hemd
- ☐ T-shirt
- ☐ Shirt met lange mouwen

Schoenen, sokken

- ☐ Enkelsokken
- ☐ Hoge sokken
- ☐ Dunne panty
- ☐ Dikke panty
- ☐ Schoenen, dunne zool
- ☐ Schoenen, dikke zool
- ☐ Laarzen

Broeken

- ☐ Korte broek

- ☐ Lange zomerbroek, dunne stof
- ☐ Normale lange broek (bijvoorbeeld een spijkerbroek)
- ☐ Warme lange broek, dikke stof

- ☐ Legging
- ☐ Overall

Shirts / bloezen

- ☐ T-shirt of blouse zonder mouwen
- ☐ T-shirt of blouse met korte mouwen

- ☐ Zomershirt met lange mouwen
- ☐ Normaal shirt met lange mouwen
- ☐ Warm shirt met lange mouwen
- ☐ Blouse of overhemd met lange mouwen

Jurken en rokken

- ☐ Dunne rok, lichte stof
- ☐ Warme rok, dikke stof

- ☐ Dunne jurk zonder mouwen
- ☐ Dunne jurk met korte mouwen
- ☐ Dunne jurk met lange mouwen
- ☐ Winterjurk zonder mouwen
- ☐ Winterjurk met korte mouwen,
- ☐ Winterjurk met lange mouwen

Truien

- ☐ Vest zonder mouwen
- ☐ Vest met korte mouwen
- ☐ Vest met lange mouwen
- ☐ Dunne trui
- ☐ Normale trui
- ☐ Warme trui
- ☐ Colbert / jasje (dun)
- ☐ Colbert / jasje

Middag

9. Hoe voel je je op dit moment?

☐	☐	☐	☐	☐	☐	☐
Heet	Warm	Een beetje warm	Niet warm, niet koud	Een beetje koel	Koel	Koud

10. Hoeveel tocht voel je?

☐	☐	☐	☐	☐	☐	☐
Helemaal geen tocht		Een beetje tocht		Last van tocht		Veel last van tocht

11. Wat heb je het afgelopen uur vooral gedaan?

- ☐ Vooral rustig zitten, lezen
- ☐ Vooral zitten, schrijven of knutselen
- ☐ Veel staan of rondlopen

12. Vind je de temperatuur binnen acceptabel?

- ☐ Ja, acceptabel
- ☐ Nee, niet acceptabel

Vragenlijst docent Naam:........................ Datum:........................

Ochtend Tijd: ....

1. Hoe voelt u zich op dit moment?

☐	☐	☐	☐	☐	☐	☐
Heet	Warm	Een beetje warm	Niet warm, niet koud	Een beetje koel	Koel	Koud

2. Hoeveel tocht voelt u?

☐	☐	☐	☐	☐	☐	☐
Helemaal geen tocht		Een beetje tocht		Last van tocht		Veel last van tocht

3. Wat was (grotendeels) uw eigen activiteit het afgelopen uur?
   - ☐ Rustig zitten, lezen etc.
   - ☐ Zittend werk, nakijken etc.
   - ☐ Rondlopen, helpen leerlingen etc.
4. Vindt u de temperatuur binnen acceptabel?
   - ☐ Ja, acceptabel
   - ☐ Nee, niet acceptabel
5. Waren er eventuele bijzondere activiteiten (verjaardag etc.)
   - ☐ Ja, namelijk..
   - ☐ Nee
6. Zijn er momenteel ramen, ventilatieroosters, of deuren geopend? En hoe ver zijn deze geopend?
   - ☐ Aantal open ramen .... Hoever geopend? ☐ Kier ☐ Gedeeltelijk ☐ Volledig
   - ☐ Aantal open roosters .... Hoever geopend? ☐ Kier ☐ Gedeeltelijk ☐ Volledig
   - ☐ Aantal open deuren .... Hoever geopend? ☐ Kier ☐ Gedeeltelijk ☐ Volledig
7. Wat is de stand van de zonwering?
   - ☐ Volledig in gebruik
   - ☐ Niet in gebruik
   - ☐ Deels in gebruik, namelijk..
   - ☐ N.v.t.
8. Is de stand van de mechanische ventilatie het afgelopen dagdeel aangepast?
   - ☐ Ja, hoger gezet ☐ Ja, lager gezet
   - ☐ Niet aangepast ☐ Aanpassen niet mogelijk
   - ☐ N.v.t.
9. Is de stand van de thermostaat / radiatorknop het afgelopen dagdeel aangepast?
   - ☐ Ja, warmer/open ☐ Ja, kouder/dicht
   - ☐ Niet aangepast ☐ Aanpassen niet mogelijk
   - ☐ N.v.t.

Kleding

10. Geef a.u.b. hieronder aan welke kledingstukken u aanhebt.

Ondergoed

☐ Onderbroek (evt. incl. BH)
☐ Boxershort
☐ Hemd
☐ T-shirt
☐ Shirt met lange mouwen

Schoenen, sokken

☐ Enkelsokken
☐ Hoge sokken
☐ Dunne panty
☐ Dikke panty
☐ Schoenen, dunne zool
☐ Schoenen, dikke zool
☐ Laarzen

Broeken

☐ Korte broek

☐ Lange zomerbroek, dunne stof
☐ Normale lange broek (bijvoorbeeld een spijkerbroek)
☐ Warme lange broek, dikke stof

☐ Legging
☐ Overall

Shirts / bloezen

☐ T-shirt of blouse zonder mouwen
☐ T-shirt of blouse met korte mouwen

☐ Zomershirt met lange mouwen
☐ Normaal shirt met lange mouwen
☐ Warm shirt met lange mouwen
☐ Blouse of overhemd met lange mouwen

Jurken en rokken

☐ Dunne rok, lichte stof
☐ Warme rok, dikke stof

☐ Dunne jurk zonder mouwen
☐ Dunne jurk met korte mouwen
☐ Dunne jurk met lange mouwen
☐ Winterjurk zonder mouwen
☐ Winterjurk met korte mouwen,
☐ Winterjurk met lange mouwen

Truien

☐ Vest zonder mouwen
☐ Vest met korte mouwen
☐ Vest met lange mouwen
☐ Dunne trui
☐ Normale trui
☐ Warme trui
☐ Colbert / jasje (dun)
☐ Colbert / jasje

Middag Tijd: ....

11. Hoe voelt u zich op dit moment?

☐	☐	☐	☐	☐	☐	☐
Heet	Warm	Een beetje warm	Niet warm, niet koud	Een beetje koel	Koel	Koud

12. Hoeveel tocht voelt u?

☐	☐	☐	☐	☐	☐	☐
Helemaal geen tocht		Een beetje tocht		Last van tocht		Veel last van tocht

13. Wat was (grotendeels) uw eigen activiteit het afgelopen uur?

☐ Rustig zitten, lezen etc.
☐ Zittend werk, nakijken etc.
☐ Rondlopen, helpen leerlingen etc.

14. Vindt u de temperatuur binnen acceptabel?

☐ Ja, acceptabel
☐ Nee, niet acceptabel

15. Waren er eventuele bijzondere activiteiten (verjaardag etc.)
   - ☐ Ja, namelijk..
   - ☐ Nee
16. Zijn er momenteel ramen, ventilatieroosters, of deuren geopend? En hoe ver zijn deze geopend?
   - ☐ Aantal open ramen .... Hoever geopend? ☐ Kier ☐ Gedeeltelijk ☐ Volledig
   - ☐ Aantal open roosters .... Hoever geopend? ☐ Kier ☐ Gedeeltelijk ☐ Volledig
   - ☐ Aantal open deuren .... Hoever geopend? ☐ Kier ☐ Gedeeltelijk ☐ Volledig
17. Wat is de stand van de zonwering?
   - ☐ Volledig in gebruik
   - ☐ Niet in gebruik
   - ☐ Deels in gebruik, namelijk...
   - ☐ N.v.t.
18. Is de stand van de mechanische ventilatie het afgelopen dagdeel aangepast?
   - ☐ Ja, hoger gezet ☐ Ja, lager gezet
   - ☐ Niet aangepast ☐ Aanpassen niet mogelijk
   - ☐ N.v.t.
19. Is de stand van de thermostaat / radiatorknop het afgelopen dagdeel aangepast?
   - ☐ Ja, warmer/open ☐ Ja, kouder/dicht
   - ☐ Niet aangepast ☐ Aanpassen niet mogelijk
   - ☐ N.v.t.

Als u andere kleding aan heeft dan vanochtend, dit graag aangegeven in de vragenlijst. Wel erbij zetten wat voor de middag ingevuld is.

Mochten er vandaag kinderen i.v.m. ziekte afwezig zijn geweest, of gedurende de dag naar huis zijn gegaan, wilt u dit dan a.u.b. hieronder aangeven.
Ruimte voor opmerkingen: ....
....
....

A2. Introduction

The human body usually has a core temperature of 37°C. To keep this temperature as constant as possible, the body needs to be in thermal balance with the environment. This means the heat transfer to the environment needs to be equal to the internal heat production. The heat production and transfer to the environment can be classified to different categories, which are all influenced by various environmental and personal factors. This can be seen in the table below, and (slightly different) as an illustrated version in Figure 1.

In Table 1 the environmental elements t_a (air temperature), $\bar{t}_r$ (mean radiant temperature), v_a (air velocity) and p_a (absolute humidity of the air, partial pressure of water vapor) are included. The other four elements are the personal factors I_{cl} (insulation of clothing), R_{cl} (evaporative resistance of clothing), M (metabolism) and W (external work).

TABLE 1: ELEMENTS IN THE THERMAL BALANCE [1]

	t_a	$\bar{t}_r$	v_a	p_a	I_{cl}	R_{cl}	M	W
Internal heat production							x	x
Heat transfer by radiation		x			x			
Heat transfer by convection	x		x		x			
Heat losses through evaporation								
-from the skin			x	x		x	x	
-by respiration				x				
Convection by respiration	x						x	

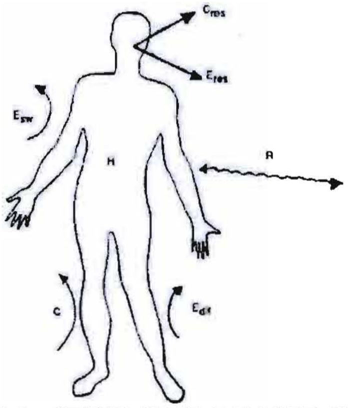


FIGURE 1: STATIC HEAT BALANCE OF THE HUMAN BODY [2]

Fanger's comfort equation is the basis for the Predicted Mean Vote (PMV) method. This PMV is the predicted average thermal sensation for a large group of persons, on the seven point scale of +3 to -3 which can be seen in Table 2. The calculation of the PMV takes into account the thermo physiological properties of humans and their thermal balance with the environment. On a personal level this includes the activity level and clothing insulation. The thermal environment is determined by the variables air temperature, mean radiant temperature, relative humidity and air velocity. Fanger's comfort equation is derived from extensive climate chamber research. The responses of over a thousand European and American subjects to the thermal conditions in a well-controlled environment were determined. This equation and the PMV model are intended for use in the design of HVAC systems. This means that for naturally ventilated, free-running buildings, the model might not be applicable.

The PMV can also be transferred to the Predicted Percentage Dissatisfied (PPD), which is the predicted percentage of people in a large group that will be dissatisfied at a PMV value. A PMV of 0 does not mean every individual has thermal neutrality, so even then the PPD is not zero.

TABLE 2: SEVEN-POINT THERMAL SENSATION SCALE [3]

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

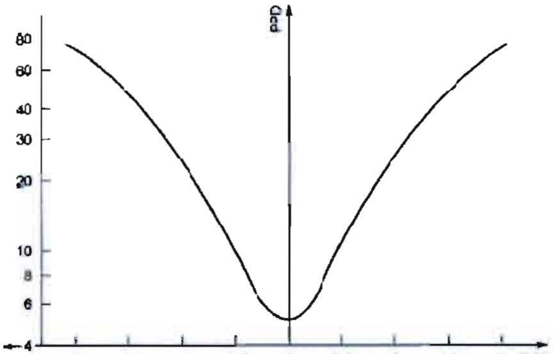


FIGURE 2: PREDICTED PERCENTAGE DISSATISFIED AS A FUNCTION OF PREDICTED MEAN VOTE [3]

A2.1. *Background research on influence of variables on PMV*

The exterior air temperature changes during the year. The interior temperature usually partly follows this change, especially within naturally ventilated buildings. The interior temperature should, however, always remain within a certain comfortable range. Practically all buildings have a form of thermal control (heating and/or cooling) for the interior temperature, for which the control is based on air temperature. Even though most attention is given to this air temperature, there are many more factors which influence thermal sensation. The influence of variables on the PMV is investigated in the following section.

Unless stated otherwise, all figures in this section are calculated for a metabolic rate of 1.2 met, clothing insulation of 0.8 clo, air speed of 0.1 m/s, relative air humidity of 50%, and external work of 0 W. All air temperatures are equal to radiant temperatures, and are stated as Operative temperatures in °C. In practice the radiant temperature must not differ too much from the air temperature; the difference should stay below 5°C. If there is a larger difference between radiant temperature and air temperature this might lead to local thermal discomfort. Discomfort caused by this or by asymmetrical radiation does not show in the PMV results. The operative temperature has a significant influence on the thermal sensation predictions, as can be seen in all the figures in this section.

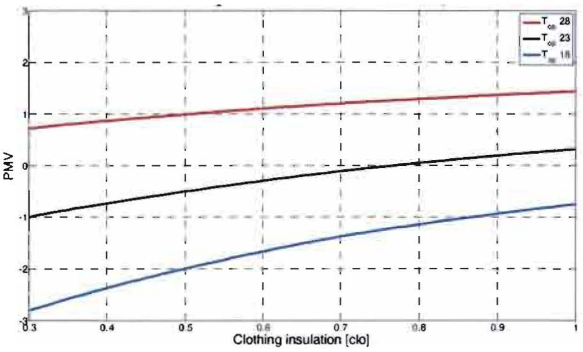


FIGURE 3: INFLUENCE OF CLOTHING INSULATION ON THERMAL SENSATION PREDICTIONS, FOR VARIOUS OPERATIVE TEMPERATURES

The influence of clothing insulation is affected by operative temperature; the influence of the clothing insulation is higher at lower temperatures. Clothing insulation has most influence at lower temperatures, since there is more heat transfer from the human body to the thermal environment because of the larger temperature difference. This can also be seen in the PMV based comfort limits, where the operative temperature range at low external temperatures is wider than at high external temperatures.

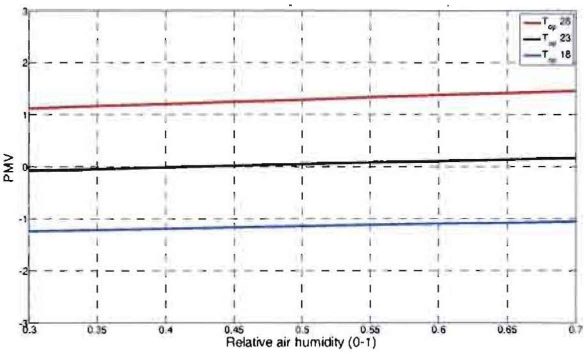


FIGURE 4: INFLUENCE OF RELATIVE AIR HUMIDITY ON THERMAL SENSATION PREDICTIONS, FOR VARIOUS OPERATIVE TEMPERATURES

In [3] it is stated that the influence of humidity on thermal sensation is small at moderate temperatures and activities. As can be seen in the figures, at higher operative temperatures this effect is slightly larger than at low temperatures, but within this range of operative temperatures of 18 - 28°C the influence is always negligible. The effect at higher temperatures is slightly higher because heat transfer by convection is not as effective at higher air temperatures, making the heat loss through evaporation a more important factor of the heat balance.

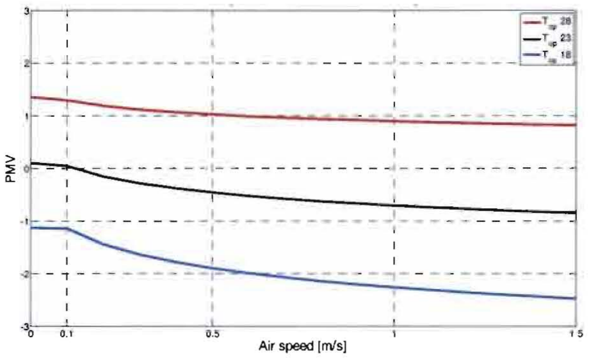
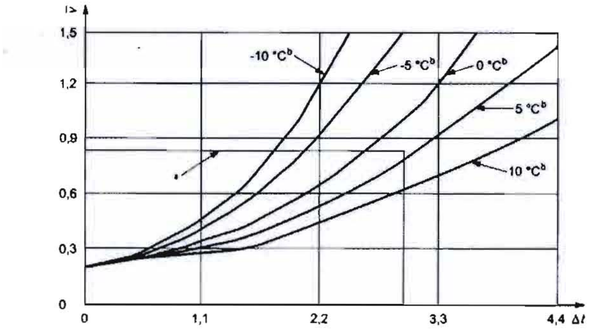


FIGURE 5: INFLUENCE OF AIR SPEED ON THERMAL SENSATION PREDICTIONS, FOR VARIOUS OPERATIVE TEMPERATURES

Air velocity has a large influence on thermal sensation predictions by PMV, especially at low operative temperatures. Increasing air speed increases the heat transfer by convection, which is larger at low temperatures. User acceptance of the increased air speed requires them to have control of the device creating the local air speed; otherwise air speeds above 0.8 m/s have a large risk of causing (local) discomfort by draft. At the temperature of 18°C increasing the air speed from 0 to 1.5 m/s lowers the PMV by 1.3 scale points. At the temperature of 28°C this is 0.5. Air speed changes between 0.1 and 0.3 m/s have the most effect. At air speeds below 0.1 m/s the air velocity has less influence on the predicted mean vote, because free convection has a relatively larger influence at low air speeds.

NEN-EN 15251 [4] also shows that air speed can be used to offset operative temperature increases. However, the amount of offset shown here is much larger than by the PMV calculations shown earlier. Also, no indication is given of the absolute air temperature at which this offset can be realised. ISO 7730:2005 [3] is referenced by EN 15251 for this figure, here it is stated that the temperature offset is for temperatures above 26°C. Also, the difference between air temperature and radiant temperature has a large influence on this, as can be seen in the figure below.



For light primarily sedentary activity, Δt should be < 3 °C and $\bar{v}$ < 0,82 m/s.

Key

Δt temperature rise above 26 °C

$\bar{v}$ mean air velocity, m/s

[a] Limits for light, primarily sedentary, activity.

[b] $(\bar{t}_r - t_a)$, °C (t_a, air temperature, °C; $\bar{t}_r$, mean radiant temperature, °C)

FIGURE 6: AIR SPEEDS REQUIRED TO OFFSET INCREASED TEMPERATURE [3]

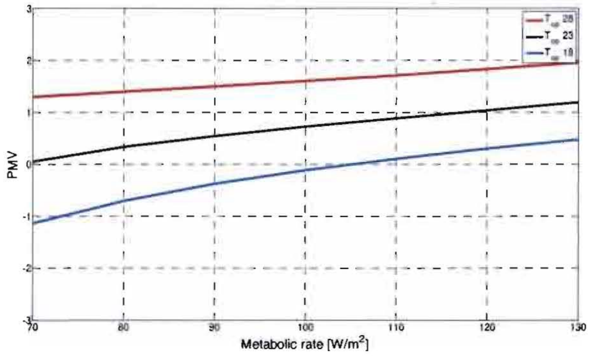


FIGURE 7: INFLUENCE OF METABOLIC RATE ON THERMAL SENSATION PREDICTIONS, FOR VARIOUS OPERATIVE TEMPERATURES

The metabolic rate has a large influence on thermal sensation predictions by the PMV model. The metabolic rates shown in the figures above cover the range of 'low metabolic rate' from ISO 8996:2004 [5]. So even though this all falls within the same category of activity, the difference in PMV can be about 1.6 scale points at a temperature of 18°C. At a temperature of 28°C the influence is less, but still about 0.7 scale points.

A3. Method

A3.1. *Schools*

All classrooms have radiators for heating, a digital blackboard and at least one computer or laptop. The classrooms are all located on the top floor of the building, and all three buildings have a flat roof.

TABLE 3: SCHOOL AND CLASSROOM CHARACTERISTICS

	De Driesprong	De Trinoom	De Korenaar
Address	Tafelbergplein 8 Eindhoven	Don Boscostraat 2 Eindhoven	Vitruviusweg 41 Eindhoven
Year built	2002	1994, renovated 2009	1964
Room dimensions	53 m^2, 159 m^3	70 m^2, 210 m^3	65 m^2, 215 m^3
Children in classroom	18	30	31
Heating	Radiators	Radiators	Radiators
Heating Control	Radiator valve, not individually controlled	Radiator valve, local cooling unit in summer	Radiator valve, not individually controlled
Ventilation	Operable windows + façade grills, Mechanical exhaust	Operable windows + façade grills, Mechanical exhaust	Operable windows
Ventilation Control	Mechanical centrally controlled Windows personal/teacher control	Mechanical only active in summer, centrally controlled Windows personal/teacher control	Windows personal/teacher control
Glazing	Double	Double	Single
Window orientation & area	West, 11 m^2	East, 12 m^2	West 17 m^2 & East 17 m^2
Solar shading	Small roof projection, curtains inside	(Vertical) Screens outside	Venetian blinds inside
Roof	Flat	Flat	Flat

In two of the three schools the heating is not controlled by the teacher or children, but only by the building manager. Windows and sunscreen/curtains are operable by the teachers and children.

A3.1.1. Driesprong

The setpoint for heating is 21°C. Outside of school hours the temperature is lowered. In the summer the heating is fully deactivated (manually) since there were some cases where the heating was still activate at high indoor temperatures. The building manager believes that the capacity of the mechanical ventilation is much too low, and has almost no influence.

The west façade is glazed from about 1.20 meter up to the ceiling, with ventilation grills. There are two separate dual-hinged windows. The east wall consists of a glass pane with a glass sliding door, which opens to a gallery in the central hall.

A3.1.2. Trinoom

The setpoint for heating is 18°C in winter and 15°C in summer. In practice this will mean that heating is inactive in summer, since temperatures will rise above this setpoint from solar and internal gains. Outside of school hours the temperature is lowered. A large part of the east wall is glazed from about 1 meter up to the ceiling, with ventilation grates. Operable sliding windows are available.

In the summer period a local airconditioning unit with a maximum cooling capacity of 3.8 kW was placed in the classroom. In this season the windows were kept closed, and the mechanical exhaust was set to maximum capacity. The CO_2 concentration stayed below 1200ppm, so the mechanical exhaust was sufficient. The indoor temperature still seemed free-running, so the influence of this cooling was minimal.

A3.1.3. Korenaar

The hall of this school was renovated in 2003, but the classroom is in the part of the building that was built in 1964. The setpoint for heating is 17-18°C for all seasons. Outside of school hours the temperature is lowered. The east and west walls both have windows and radiators over the full width, with the window-sill at a height of about 0.8 meter.

There are many operable windows, equally distributed over the east and west walls. The top windows (total 6), have a horizontal hinge. The lower windows (12 in total) have a vertical hinge.

A3.2. ***Questionnaires background; Clothing assumptions***

Garment insulation values from ISO 7730:2005 [3] were used, with some simplifications and additions of other garment possibilities which are described below. The aim was to keep the questionnaire easy-to-understand and not too long. To do this, clothing which was not expected to be worn was excluded from the list. Also, for t-shirts vests and dresses three variants were included, sleeveless, short sleeve and longsleeve.

Table C.2 in ISO 7730:2005 shows 'socks, clo=0.02', 'thick, ankle socks, clo=0.05' and 'thick, long socks, clo=0.1'. This was simplified for the questionnaire into socks (clo=0.1) and ankle socks (clo=0.02).

Not all possible shirts are included in ISO 7730:2005, but since excluding some possibilities might lead to an unclear questionnaire assumptions were made for the clo values of these garments. For unknown clo values, the most comparable garment was used and adapted. This adaptation was done so the difference between sleeveless and short sleeve was 0.05 clo, and between short and longsleeve 0.03 clo. With this, a sleeveless t-shirt was assumed to be 0.10 clo, short-sleeve vest 0.17, long-sleeve vest 0.20, light dress-sleeveless 0.15, light dress-long sleeve 0.23, winter dress-sleeveless 0.32, winter dress-short sleeve 0.37.

For slippers an insulation value of 0.01 was assumed. These were worn by nearly all children during the summer measurements, and added as an option by themselves. Shoes with a thin sole have an insulating value of 0.02. A legging and thick stockings were also included, both for 0.20 clo which is equal to light pants. All other clothing garments which are on the questionnaire can be found in ISO 7730:2005.

Chair insulation of 0.01 clo was added for the open wooden chairs used in the classrooms.

The total garment list used is included below, with corresponding insulating values. When this value is in italic font, it is not included in ISO 7730.

Ondergoed

☐ Onderbroek (evt. incl. BH) [0.03]
☐ Boxershort [0.10]
☐ Hemd [0.04]
☐ T-shirt [0.09]
☐ Shirt met lange mouwen [0.12]

Schoenen, sokken

☐ Enkelsokken [0.02]
☐ Hoge sokken [0.10]
☐ Dunne panty [0.03]
☐ Dikke panty *[0.20]*
☐ Schoenen, dunne zool [0.02]
☐ Schoenen, dikke zool [0.04]
☐ Laarzen [0.10]

Broeken

☐ Korte broek [0.06]

☐ Lange zomerbroek, dunne stof [0.20]
☐ Normale lange broek (bijvoorbeeld een spijkerbroek) [0.25]
☐ Warme lange broek, dikke stof [0.28]

☐ Legging *[0.20]*
☐ Overall [0.55]

Shirts / bloezen

☐ T-shirt of blouse zonder mouwen *[0.10]*
☐ T-shirt of blouse met korte mouwen [0.15]

☐ Zomershirt met lange mouwen [0.20]
☐ Normaal shirt met lange mouwen [0.25]
☐ Warm shirt met lange mouwen [0.30]
☐ Blouse of overhemd met lange mouwen [0.15]

Jurken en rokken

☐ Dunne rok, lichte stof [0.15]
☐ Warme rok, dikke stof [0.25]

☐ Dunne jurk zonder mouwen *[0.15]*
☐ Dunne jurk met korte mouwen [0.20]
☐ Dunne jurk met lange mouwen *[0.23]*
☐ Winterjurk zonder mouwen *[0.32]*
☐ Winterjurk met korte mouwen *[0.37]*
☐ Winterjurk met lange mouwen [0.40]

Truien

☐ Vest zonder mouwen [0.12]
☐ Vest met korte mouwen *[0.17]*
☐ Vest met lange mouwen *[0.20]*
☐ Dunne trui [0.20]
☐ Normale trui [0.28]
☐ Warme trui [0.35]
☐ Colbert / jasje (dun) [0.25]
☐ Colbert / jasje [0.35]

A3.3. *Measurement equipment*

Measurement setup per school

Measurement setup 1	De Driesprong
Measurement setup 2	De Trinoom
Measurement setup 3	De Korenaar

Parameter	Measurement setup 1		Measurement setup 2		Measurement setup 3	
	TU/e ID nummer	Logger Channel	TU/e ID nummer	Logger Channel	TU/e ID nummer	Logger Channel
Logger	443	*type Eltek*	444	*type Eltek*	1940	*type Grant*
T_{globe}	1250	1	610	1	1248	8
CO_2	329	3	395 / 341	3	327	9
T	766	4	765	4	591	10
RV	766	5	765	5	591	11
v	837	6	708	6	838	12
T	837	7	708	7	838	13

Temperature values from ID837, ID708 and ID838 (air velocity sensors) were not used. CO_2 concentrations were reported to the schools, but not used in the further research.

Variable	Measurement setup 1			
	Output	Range	Accuracy	Function x = sensor output
T_{globe}	-200 to 100 [°C]	-200 to 100 [°C]	Unknown	$T = x$
CO_2	0 – 10 [V]	0 – 5000 [ppm]	±30 ppm + 2% of reading	$CO_2 = -2.1807 * x^2 + 501.82 * x - 14.469$
T	0 – 1 [V]	-5 – 55 [°C]	±0.5°C for -5-55°C ±0.2°C at 20°C	Linear $T = 60 * x - 5$
RV	0 – 1 [V]	0 – 100 [%]	±2% RH for 0-90% and 10-40°C Tair	Linear $RV = 100 * x$
v Omnidirectional, spherical	0 – 5 [V]	0,05 – 5 [m/s]	Range 0.05 to 1 m/s 0.02 m/s ±1% of readings Range of 1 to 5 m/s ±3% of readings	*Specified below*

Variable	Measurement setup 2			
	Output	Range	Accuracy	Function
T_{globe}	-200 to 100 [°C]	-200 to 100 [°C]	Unknown	$T = x$
CO_2 *(395)*	0 – 10 [V]	0 – 5000 [ppm]	±30 ppm + 2% of reading	$CO_2 = -4.2978 * x^2 + 653.42 * x + 244.85$
CO_2 *(341)*	0 – 10 [V]	0 – 2000 [ppm]	±30 ppm + 2% of reading	$CO_2 = 172.69 * x + 100.67$
T	0 – 1 [V]	-5 – 55 [°C]	±0.5°C for -5-55°C ±0.2°C at 20°C	Linear $T = 60 * x - 5$
RV	0 – 1 [V]	0 – 100 [%]	±2% RH for 0-90% and 10-40°C Tair	Linear $RV = 100 * x$
v Omnidirectional, spherical	0 – 5 [V]	0,05 – 5 [m/s]	Range 0.05 to 1 m/s 0.02 m/s ±1% of readings Range of 1 to 5 m/s ±3% of readings	*Specified below*

Variable	Measurement setup 3			
	Output	Range	Accuracy	Function
T_{globe}	-200 to 200 [°C]	-200 to 100 [°C]	Unknown	$T = x$
CO_2	0 – 10 [V]	0 – 5000 [ppm]	±30 ppm + 2% of reading	$CO_2 = -4.8715 * x^2 + 518.56 * x - 28.624$
T	0 – 10 [V]	0 – 50 [°C]	Unknown	Linear $T = 5 * x$
RV	0 – 10 [V]	0 – 100 [%]	Unknown	Linear $RV = 10 * x$
v Omnidirectional, spherical	0 – 5 [V]	0,05 – 5 [m/s]	Range 0.05 to 1 m/s 0.02 m/s ±1% of reading Range of 1 to 5 m/s ±3% of reading	*Specified below*

A3.4. *Air speed calculation .m-file*

A matlab .m file was created to calculate the air speed, using volts and TU/e ID number as input variables. This code is based on calibration data of the three air velocity sensors, and is included below.

```
function y=airvelocity(x,n)
% Calculate the air velocity.
% x= volt value
% n= TU/e ID number

F15=x;

if n==708
    if F15<1.59
        G7=-0.110904488;
        G8=-0.356772307;
        G9=0.182420969;
        G10=-0.069208001;
        G11=0.010075609;
    else
        G7=0.220527766;
        G8=0.146642836;
        G9=-0.00676411;
        G10=0.000366086;
        G11=-0.0000075232203627254;
    end
    y=(G7+G8*F15^2+G9*F15^4+G10*F15^6+G11*F15^8)^2;
end

if n==837
    if F15<1.548
        G7=-1.0623E-01;
        G8=-4.1623E-01;
        G9=2.5481E-01;
        G10=-1.0301E-01;
        G11=1.5599E-02;
    else
        G7=2.2381E-01;
        G8=1.4513E-01;
        G9=-5.3538E-03;
        G10=1.9669E-04;
        G11=-2.5662E-06;
    end
    y=(G7+G8*F15^2+G9*F15^4+G10*F15^6+G11*F15^8).^2;
end

if n==838
    if F15<1.551
        G7=-1.0485E-01;
        G8=-3.7072E-01;
        G9=1.8783E-01;
        G10=-6.8528E-02;
        G11=9.5554E-03;
    else
        G7=2.3163E-01;
        G8=1.4009E-01;
        G9=-4.6971E-03;
        G10=1.6199E-04;
        G11=-1.8253E-06;
    end
    y=(G7+G8*F15^2+G9*F15^4+G10*F15^6+G11*F15^8)^2;
end
```

A4. Results

A4.1. *Results for the schools*

The schools were given a short report of the results for each measurement period for their own classroom. In these reports the demands from ISSO 89 [6] were given and explained, and in the results for operative temperature and CO_2 concentration these limits were also shown in the same way as in Figure 8. These limits are given in Table 4. These limits need to be met 90% of the time. The classes A, B and C are described below.

- Class A: High expectancy pattern from building users regarding the quality of the indoor environment.
- Class B: Average expectancy pattern regarding the quality of the indoor environment.
- Class C: (approx. legal minimum level for new buildings) Low expectancy pattern regarding the quality of the indoor environment.

TABLE 4: ISSO 89 LIMITS [6]

	Class A	Class B	Class C
Operative temperature, lower limit	20 °C	20 °C	19 °C
Operative temperature, upper limit, when exterior temperature < 20 °C	22 °C	23 °C	24 °C
Operative temperature, upper limit, when exterior temperature > 20 °C	Exterior + 2 °C maximum 27 °C	Exterior + 3 °C	Exterior + 4 °C
CO2 concentration	< 800 ppm	< 900 ppm	< 1200 ppm

The CO_2 concentrations are shown for all schools in Figure 8. This figure shows the minimum, mean and maximum for each part of day, weekend and Wednesday afternoon data is not shown. It can be seen here that in the winter period concentrations above 1200 ppm were recorded. During mid-season and summer the concentrations stay lower, since windows are opened (more) in these seasons, so fresh-air supply is sufficient in these seasons.

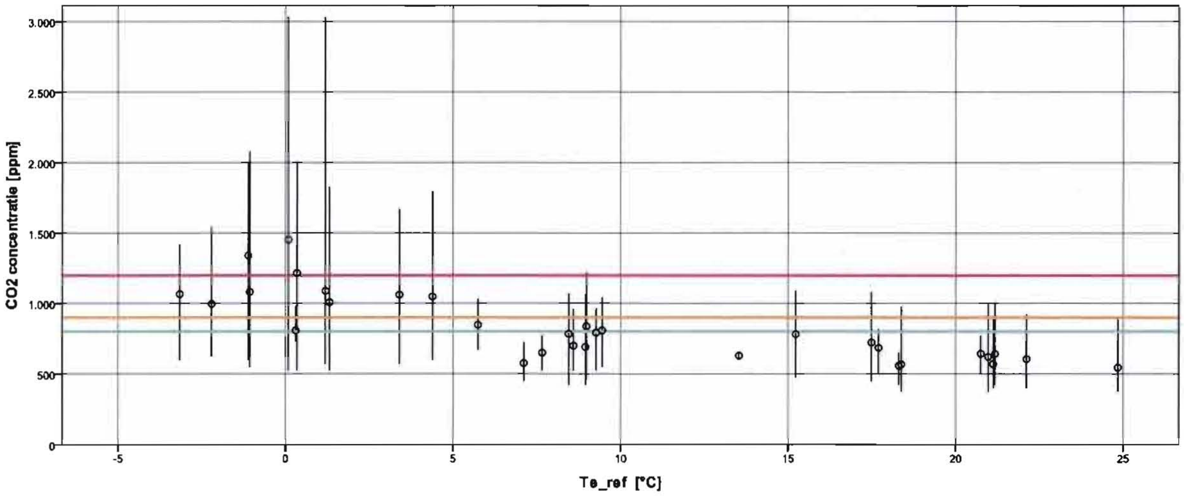


FIGURE 8: CO_2 CONCENTRATIONS FOR ALL SCHOOLS AND SEASONS

Besides the results for environmental parameters also the thermal sensation and acceptance of the children were reported to the schools.

A4.2. *Result processing*

Measurement data was loaded into Matlab (version R2009b). Data for the exterior climate was taken from the Royal Netherlands Meteorological Institute (KNMI), which was measured in Eindhoven. The daily value table was used and from the data provided the daily minimum and maximum temperatures were used, as well as the mean relative humidity.

The data from the questionnaires was put into a SPSS database.

Later, the Matlab and SPSS data were combined to be used in both programs, since both have their own advantages for certain applications.

All separate clothing garments' clo values were added to calculate the total clothing insulation for the individual. Some questionnaires were not filled in completely, or indicated clothing ensembles were not realistic. If no shoes or boots were checked, for winter and spring 0.04 clo (shoes, thick soled) is added to the total, and for summer 0.02 clo (shoes, thin soled). If no underwear is checked, 0.03 clo (panties) is added. If no socks are checked, 0.02 clo (socks) is added. If the only shirt that was checked was undergarment, this was changed to a regular shirt.

If no shirt/sweater/dress was checked, or no pants/skirt/dress was checked, the data was not included in the database. During winter, there were a few cases were only a sleeveless shirt/vest was checked, and no clothing with short or long sleeves. This data was also not included. There were no winter cases where only short pants or a skirt/dress were checked. There were a few cases where multiple sweaters, or other unrealistic combinations of garments were checked, these cases were also not included. A total of 117 cases (morning or afternoon) were disregarded for the reasons mentioned above or because no clothing indications were given, this is 5% of the total.

The chair insulation for a wooden chair, 0.01 clo, was added to the total.

Data from days with a low amount of cases (n<6) were removed, these are days where only a few children provided their thermal sensation, mostly because it is a Wednesday afternoon and the questionnaire was not centrally filled in on these afternoons. Data from teachers was recorded, but cut from the database into a separate file and not used further.

Air speed measurements for the summer period with measurement setup 3 were not recorded properly. PMV calculations were not done for these measurements.

A4.2.1. Database and Matlab files

The file FinalFile_SingleTime shows the most important variables, sorted in rows for each child, for each part of day. GraphData shows each part of day in 1 row, so no individual information. MeetwaardenGemiddeld was used for results for the schools, and includes only the measured values, but besides the mean for each part of day it also included the minimum and maximum values. AllSeasonsSingleTime shows all information, so all individual clothing garments and all information the teacher provided about operable windows etc. This file also contains the children's location in the classroom; this uses the following system of coding: A is near an operable window; B is near a fixed window; C is near the door; D is near the wall; E is a central location; F is the teacher's location; and G is in the hallway (school 2).

Some of these files are also available as a Matlab .m file using the same filenames. These are sorted in a different way, since for creating some of the figures in SPSS the row order is changed automatically.

The Matlab file compare_74_89.m creates scatterplots of Operative temperature and External climate with ISSO 74 ISSO 89 ASHRAE 55 and NEN-EN 15251 Annex A2 limits, as shown in the paper and Figure 15. The points in these plots are coloured based on AMV or Acceptance Votes. By setting the variable BLACKWHITE in row 2 to a value of 0 these figures will be coloured instead of being in grayscale, and more categories for PPD will be used. In the .m files some explanations are also given about the calculations, data loading, functions used etc.

A5. Discussion

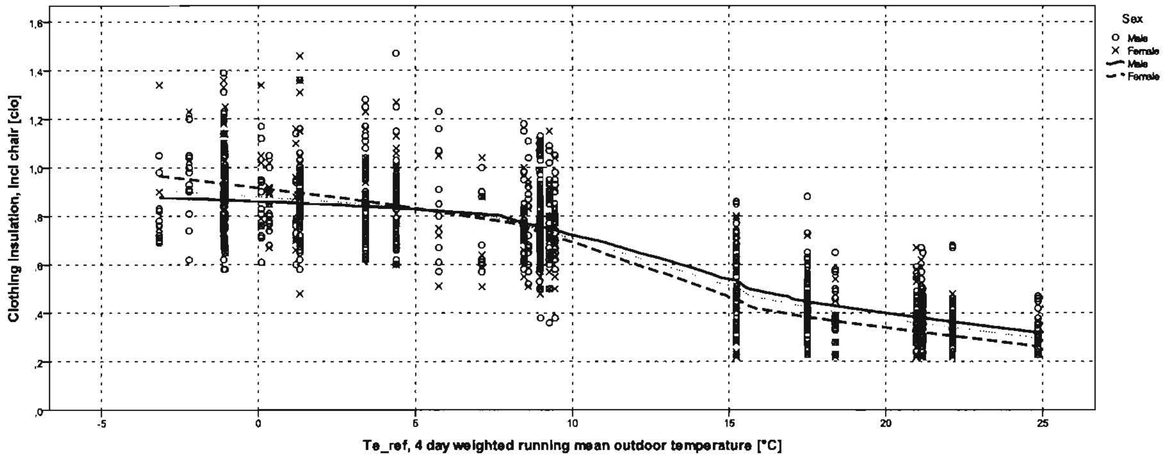
In this appendix some extra figures and information is offered to further support the discussion part of the paper.

A5.1. *Clothing insulation*

As indicated in the paper:

"There is only a small difference between male and female's clothing insulation, similar to results from a study by Humphreys [7] *where clothing for 7-9 year olds in a classroom was studied. For (mean) clothing insulation for adults in office buildings, de Carli et al* [8] *also showed a small difference between male and female, whereas Fishman and Pimbert* [9] *found a large difference. The mean clothing insulation in winter is about 0.9 clo, which is comparable to values recorded by the previously mentioned sources and de Dear et al* [10]. *This value drops to about 0.3 clo in summer, which is slightly lower than the minimum values in the previously mentioned sources, but a lot lower than the mean in* [10] *and mean for males from* [9] *at comparable exterior temperatures."*

Shown here are (some of the) figures which are referenced in the paper, as shown above with updated reference numbers.



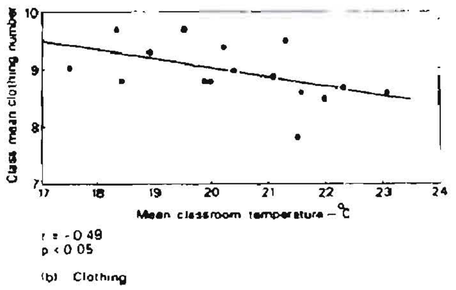


Fig. 6. Mean classroom temperatures, subjective warmth and clothing number [7]

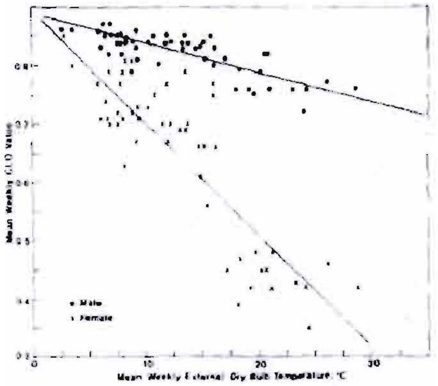
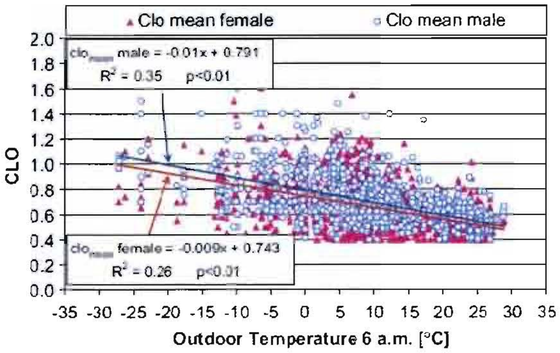
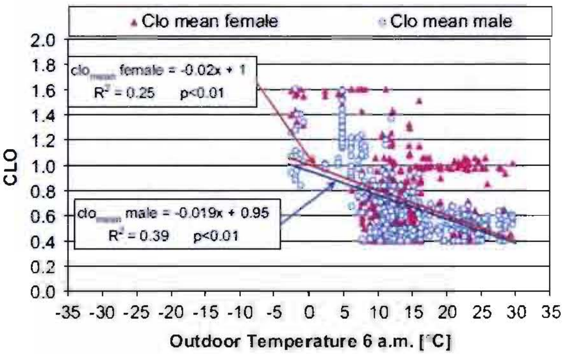


Fig. 3. Variation of average weekly clothing insulation with external ambient temperature. [9]





[8]

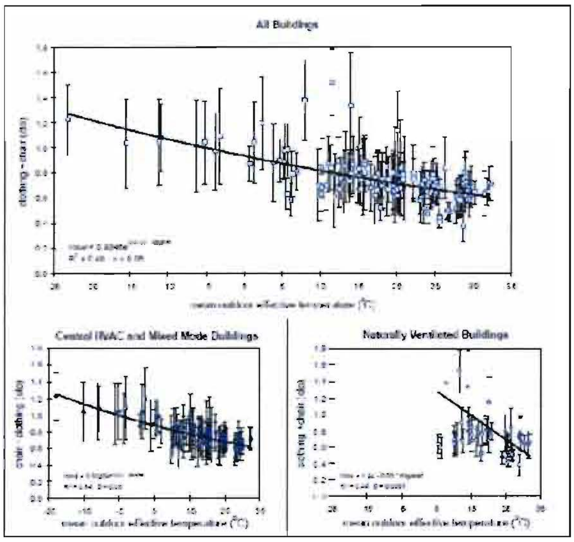
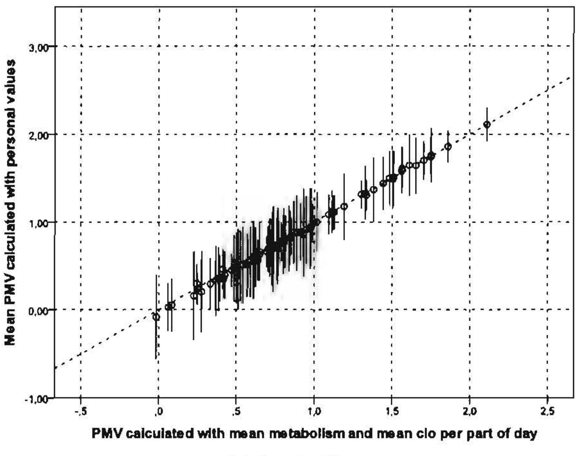


Figure 3.25 Building occupants' thermal insulation (clothing plus chair) as a function of outdoor temperature [10]

A5.2. *PMV calculations*

Shown next are some figures which support the discussion in the paper. Several conclusions from this discussion are clarified further by these figures.



Error Bars: +/- 1. SD

FIGURE 9: MEAN INDIVIDUAL PMV AND PMV WITH MEAN VARIABLES

The mean of the PMV calculated with personal values is nearly equal to the PMV calculated with mean values of metabolism and clothing insulation. The standard deviation of the individual PMV's varies from 0.2 to 0.4.

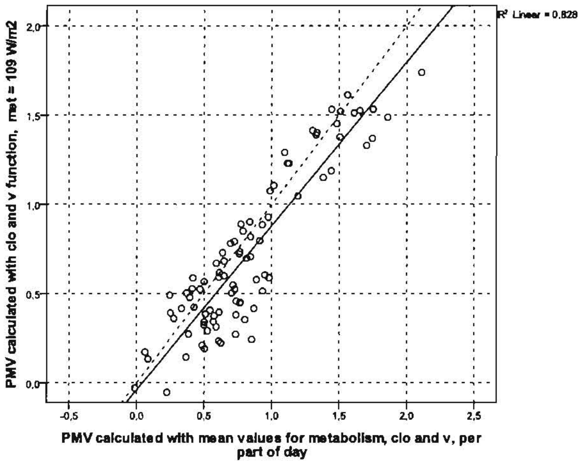


FIGURE 10: ANALYTICAL AND ADAPTIVE PMV

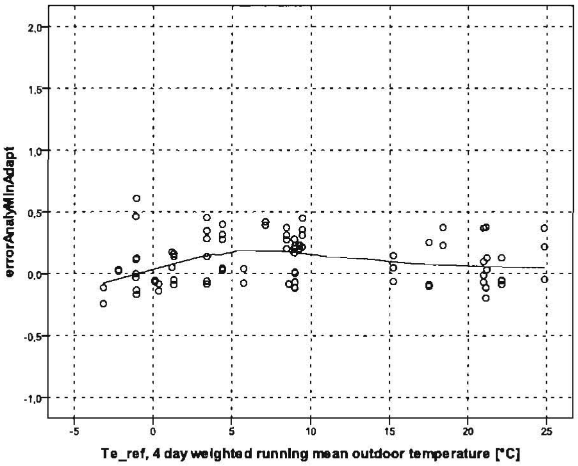


FIGURE 11: ERROR BETWEEN ANALYTICAL AND ADAPTIVE PMV

The Adaptive PMV (calculated with clo function, v function and constant met) yields results similar to the Analytical PMV (calculated with actual values). The mean difference between analytical and adaptive PMV in this situation is about 0.1 scale point. The error is slightly higher during the mid-season, likely because of large changes in clothing insulation in this period.

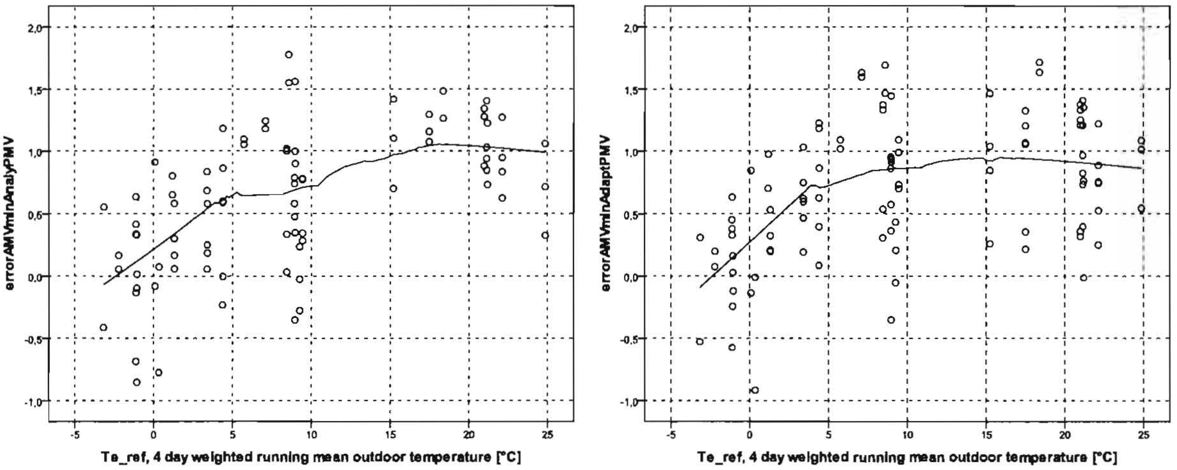


FIGURE 12: ERROR BETWEEN AMV AND ANALYTICAL PMV (L) AND BETWEEN AMV AND ADAPTIVE PMV (R)

The error of the two PMV calculations with AMV is much larger. This error is clearly largest in summer, with a predicted error of about 1 scale point at a $\theta_{e,ref}$ of 15°C or higher. Since there is a small difference between these two PMV's, as shown in Figure 11, there is also a slight difference in the error with AMV.

A5.3. *PMV based thermal comfort limits*

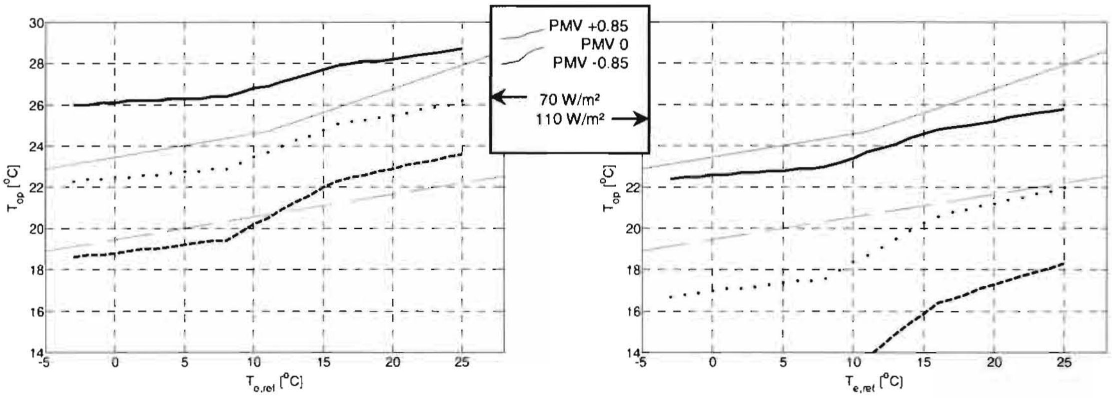


FIGURE 13: TWO VERSIONS OF ADAPTIVE PMV BASED THERMAL SENSATION LIMITS

The figures above are based on the adaptive PMV, which means that values for clothing, air speed and metabolism are predicted based on the measurement data. The clothing insulation and air velocity are shown in Figure 14. For the first figure the metabolism value is estimated to be constant at 70 W/m², which is the value for sedentary activity for adults according to ISO 7730:2005[3], and the lower limits from ISO 8996:2004 [5]. The second figure shows the same limits, only for a metabolism of 109 W/m². This is the value as estimated for the children, based on [met]*58.2*1.7/1.14 to take into account reduced body surface area of 10 year olds compared to adults. This results in a much lower minimum comfort temperature than those predicted by ISSO 74 [2]. The neutral temperature of 16.7°C at the minimum external climate seems relatively low, even though the metabolism of 110 W/m² is within the ISO 8996:2004 'low metabolic rate' range of 70-130 W/m² so for adults wearing 0.9 clo of clothing insulation, this is in fact the temperature with neutral PMV. This shows again the large influence of metabolic rate on thermal sensation, and the low accuracy of some of the activity categories.

At higher clothing insulation, temperature has less influence on thermal sensation. Therefore, the PMV limits at low external temperatures (and therefore high clothing insulation) are much wider than at high external temperatures (and low clothing insulation).

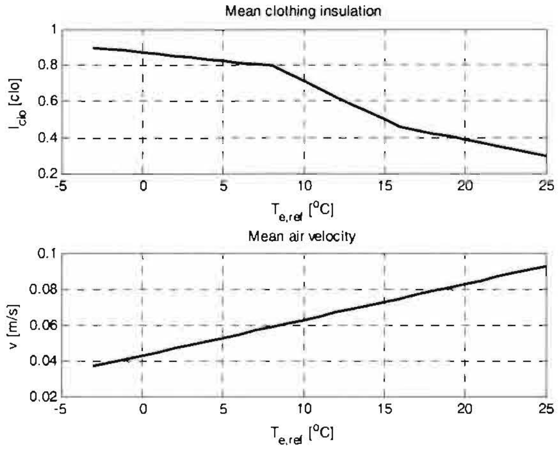


FIGURE 14: CLOTHING INSULATION AND AIR SPEEDS USED IN ADAPTIVE PMV

A5.4. *Assessment methods*

As indicated in the paper many variables are used to express the exterior climate. These are shown in the table below which is also included in the paper.

TABLE 5: VARIOUS VALUES TO EXPRESS THE EXTERIOR CLIMATE

Standard	Exterior Temperature variable	Definition
ASHRAE 55-1992	ET*	Mean daily outdoor effective temperature
ASHRAE 55-2004	$t_{a(out)}$	Monthly mean of daily min/max mean
NEN-EN 15251	θ_{rm}	Weighted running mean of daily mean, excluding current day
ISSO 74	$\theta_{e,ref}$	4 day weighted running mean of daily min/max mean, including current day
ISSO 89	θ_{bu}	Current external temperature

The effective temperature **ET*** is the temperature at which, with a relative humidity of 50%, the thermal balance would be the same as the actual current situation. This was no longer used in the updated version of ASHRAE Standard 55 [11], since the variable was not understandable for many users of the standard.

$t_{a(out)}$ is the arithmetic mean of the month's mean minimum and maximum temperatures.

θ_{rm} is described by the following formula, where θ_{rm-1} is the running mean temperature of the previous day, and θ_{ed-1} is the daily mean external temperature for the previous day.

$$\theta_{rm} = (1 - \alpha)\theta_{ed-e} + \alpha\theta_{rm-1}$$

Here, α is a constant between 0 and 1. The value recommended to be used is 0.8 [4].

The $\theta_{e,ref}$ used in ISSO 74 [2] is described by the following formula:

$$\theta_{e,ref} = \frac{\left(1\theta_{today} + 0.8\theta_{yesterday} + 0.4\theta_{day\ before\ yesterday} + 0.2\theta_{day\ before\ day\ before\ yesterday}\right)}{2.4}$$

The daily temperatures used here are the mean of the daily minimum and maximum.

The interior climate is defined in operative temperature in all of these methods. This takes into account the air temperature weighted by the convective heat transfer coefficient, and the radiant temperature weighted by the linearized radiant heat transfer coefficient. In this case this is simplified to the arithmetic mean of these temperatures, since the activity is near-sedentary (1.0 – 1.3 met), air speeds are low (below 0.20 m/s), and it is assumed that the children are not in direct sunlight.

There are some important consequences on the use of different variables to define exterior climate. θ_{rm} is slower to respond to exterior climate changes. This slow changing value makes it an indication of the season or month. It will not vary strongly for different years. $\theta_{e,ref}$ responds faster, and thereby it is more an indication of the current climate, considering it only takes onto account the current and three previous days.

A5.4.1. Assessments

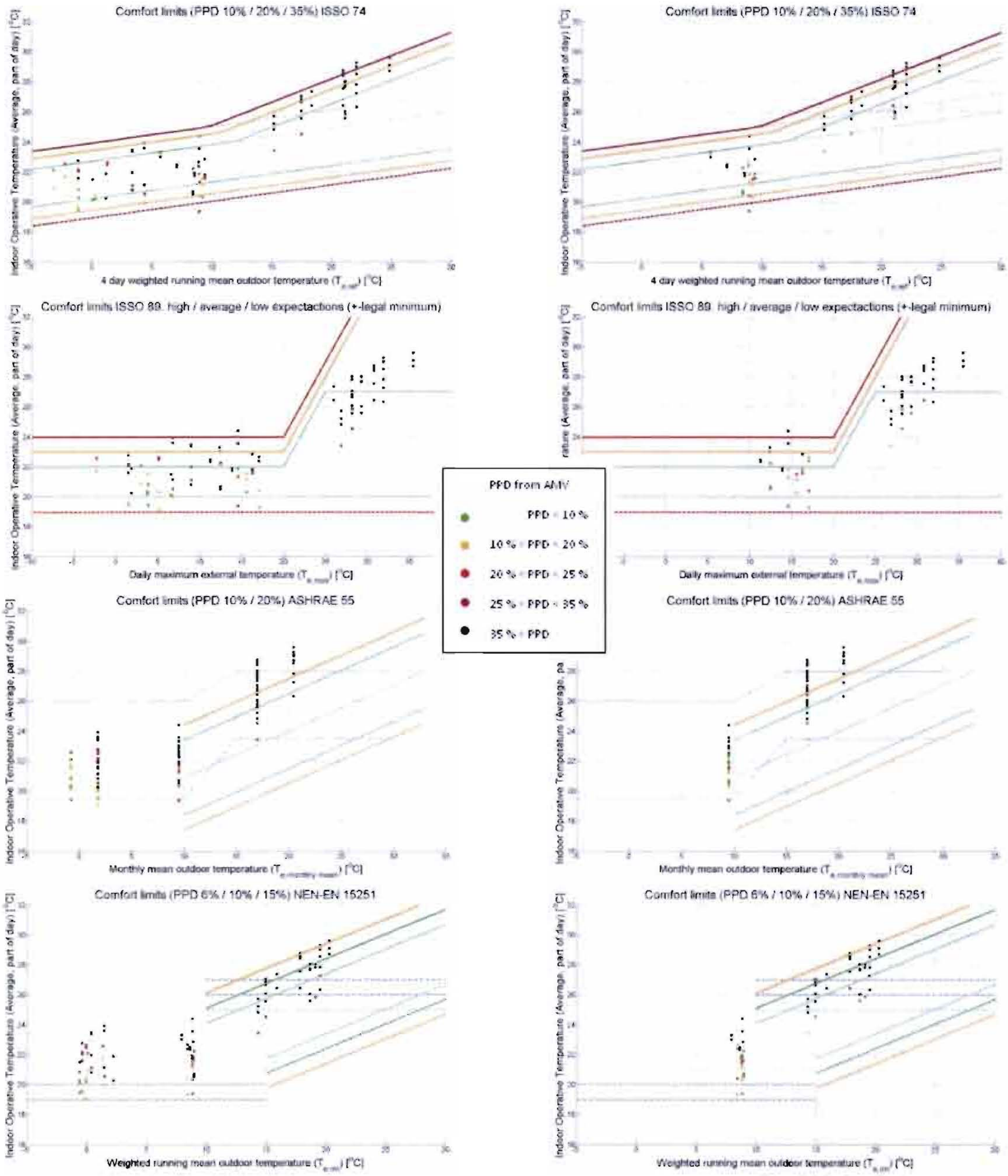


FIGURE 15: ASSESSMENT METHODS WITH INDICATION OF PPD FROM AMV (LEFT), AND THE ACTUAL PERCENTAGE DISSATISFIED (RIGHT)

The indoor temperatures measured mostly fall within all the limit's (outmost) categories, except for the ASHRAE limits where more than half of the time the upper limits are exceeded. These limits are a bit stricter than ISSO 74's (20% PPD against 35% for the outer limits), but when that is considered the ASHRAE limits still are stricter. The ISSO 89 categories B and C allow very high operative temperatures during the summer period.

The temperatures in winter do not drop below 19°C, and rise quite high in summer. The heating setpoints stated by the building managers are ranged from 17 to 21°C. The mean temperatures in winter were occasionally 3°C or more above these setpoints, which could mean that the control is not accurate on the classroom level (overshoot), there are many uncontrolled heat gains, or the setpoints specified are not correct. Off course there are many more possible causes for the higher temperatures in both winter and summer season, but it is not the goal of this research to investigate these classrooms in detail so this will not be discussed further.

The actual thermal sensations are mostly too high to be evaluated as comfortable, even though according to the standards the temperatures are. When thermal acceptance is used instead of thermal sensation in the evaluation of thermal comfort this is more comparable to the limit's predictions. Still many situations which would be evaluated as comfortable by most limits are in reality considered unacceptable by many children.

As indicated in the paper, it seems that in the summer season thermal preference lies at a lower thermal sensation than during the spring season. This is most clear when looking at the acceptance votes corresponding to a thermal sensation of +2, 'warm', see Figure 16. In the summer season there is a clear shift towards unacceptable for this vote compared to the votes in the colder season. It should be considered that the hot indoor temperatures and overall discomfort in summer might have influenced these results, but considering that this trend of cooler thermal preference for persons in warm exterior climate was also indicated by McIntyre, cited and confirmed by de Carli et al [8] it seems realistic that this trend should also be considered in this situation.

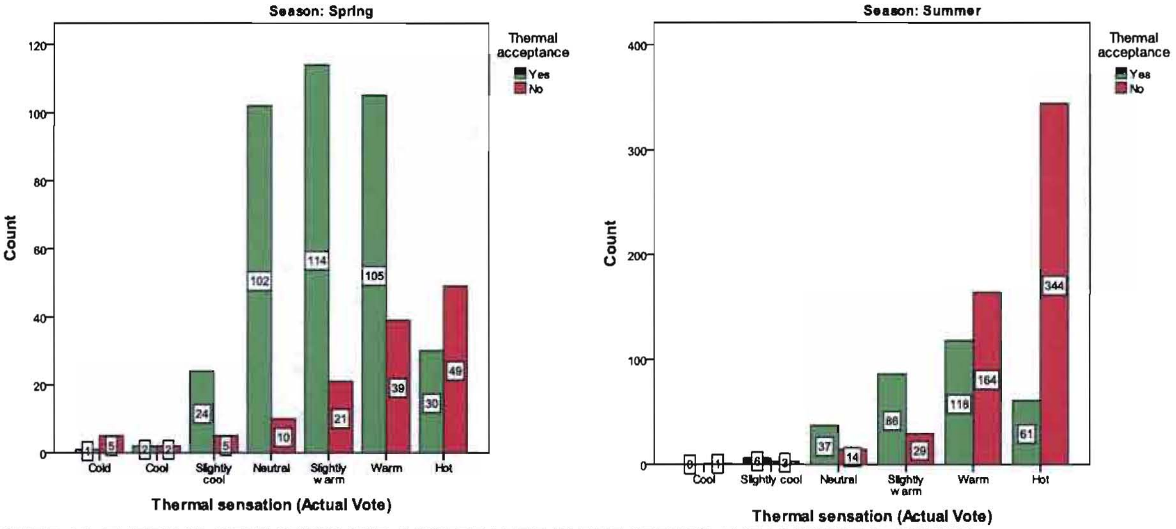


FIGURE 16: THERMAL SENSATION AND ACCEPTANCE IN THE SPRING AND SUMMER SEASONS

A6. References

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[4]. **CEN.** EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels : European Committee for Standardization, 2007.

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A7. Data sources / software used

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The Mathworks, Inc. Matlab R2009b

SPSS PASW Statistics 18