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Developing assumptions of metabolic rate estimation for primary school children in the calculation of the Fanger PMV model

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Abstract

Metabolic heat production is one of the key parameters in maintaining the body's heat balance with the environment. Levels of accuracy and methods for estimation of metabolic rate for various activities are given in most of the commonly used standards, and estimated metabolic rates for an average adult are tabulated to be used where direct measurement is not practical. However, determination of metabolic rate is expected to be different in a younger population compared with that of adults. This paper is part of a larger study that reports on the sensitivity of Predicted Mean Votes of thermal comfort to assumptions of metabolic rates, based on data from field studies in non-air conditioned primary schools in Shiraz, Iran. The outcome of the present study highlights the need for more field-based research in order to examine the accuracy of input parameters in the PMV model while predicting children's thermal sensation in the classroom.

Keywords: Metabolic rate, Thermal comfort, Predicted mean vote, Primary school children

1. Introduction

Fanger's (1970) Predicted Mean Vote (PMV) model is based on heat balance theory, and given to be a function of four environmental and two personal factors: air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and activity level i.e. internal heat production in the body (Fanger, 1973). Metabolic rate is presented in this model (ISO 7730, 2005) in the following forms: resting metabolic rate (RMR, given a value of 58.15 W/m^2 for an average adult), and MET value which is a measure of activity level (Gagge et al., 1941). The MET value is described as the metabolic rate of a given activity in proportion to the resting rate (ASHRAE, 2009).

The conversion of chemical into mechanical and thermal energy is discussed in ISO 8996 (2004) and IUPS Thermal Commission (2001). For most types of activities, mechanical work is small and can be regarded as zero especially for sedentary activities (ASHRAE, 2009); hence in ISO 8996 (2004) the rate of heat production is regarded as equivalent to metabolic rate.

Metabolic heat production is dependent on activity, person, and environment (ASHRAE, 2009). It is estimated based on body surface area or body mass, to take into account variation between individuals of different body size (Havenith et al., 2002). Havenith states that body surface area directly affects heat balance with the environment, whereas body mass contributes to heat production in "load moving activities". Therefore in the heat balance equation metabolic rate is measured in W/m^2 because heat exchange with the environment is a function of area (IUPS Thermal Commission, 2001).

According to Goto et al. (2002) "activity level is probably one of the least well-described parameters of all the parameters that affect thermal sensation, comfort and temperature preferences indoors". Metabolic rates for different activities were developed based on adults' physiology. However, age and body size affect the rate of internal heat production. This implies that children's thermal comfort assessment needs more insight into the influence of metabolic rate on the PMV calculation. This paper reviews relevant literature relating to children's metabolic rate and reports the sensitivity of the PMV model to assumptions of metabolic rates. The relationship between PMV predictions and thermal sensation during sedentary activities in the classroom is examined, to evaluate the robustness of children's MET and RMR values derived from the physiology literature.

2. Existing methods for determination of the metabolic rate

ISO 8996 (2004) provides four levels of accuracy and eight methods, where the accuracy and cost of study increase from level one to four (Table 1). As can be inferred, the methods increase in complexity. For instance, method 4B estimates average metabolic rate over longer periods (1-2 weeks); a minimum of six days is required for the test in children. Method 4C is direct calorimetry, where body heat loss is measured while performing an activity in an insulated chamber.

Table 1. Levels and methods for estimation of the metabolic rate based on ISO 8996 (2004)

Level	Method	Accuracy
1.Screening	A: Classification for different occupation	Rough information Very high risk of error
	B: Classification for type of activity	
2.Observation	A: Tables for group assessment	Accuracy: ±20% High risk of error
	B: Tables for specific activities	
3.Analysis	Determination of metabolic rate from heart rate measurement under defined conditions	Accuracy: ±10% Medium risk of error
4.Expertise	A: Determination of metabolic rate by measurement of oxygen consumption rate	Accuracy: ±5%
	B: Doubly labelled water	
	C: Direct calorimetry	

Other Standards commonly used in thermal comfort assessment tabulate metabolic rates for sedentary activities. ISO 7730 (2005) nominates the metabolic rate for seated relaxed and sedentary activity close to the estimation of metabolic rate for 'specific activities' in ISO 8996 (2004). The average metabolic rate by 'category' given in ISO 8996 (2004) suggests the 'average resting' and 'low' metabolic rate as equivalent to 65 W/m^2 and 100 W/m^2 respectively. ASHRAE 55 (2010) nominates a metabolic rate for typical seated office activities from 55-70 W/m^2 including reading seated, writing, typing, and filing while seated. For resting activity while seated quietly the ASHRAE estimate 60W/m^2.

2.1 Limitations of existing methods in the assessment of thermal comfort

Havenith et al. (2002) show that a 15% error in the estimation of metabolic rate can result in errors in PMV of 0.3 or more and conclude that "for precise comfort assessment a precise measure of metabolic rate is needed". Of the six input parameters in the calculation of the PMV model, metabolic rate is the most influential

(Gauthier and Shipworth, 2012). Hence, employing the most accurate metabolic rate in the calculation of PMV minimizes the risk of error and uncertainty.

Notwithstanding that more direct methods for determination of metabolic rate can lead to more accurate estimates, the usability of these methods in the field study of thermal comfort is debateable. These methods require special instrumentation and measurement protocols and thereby may interfere with the routine tasks and activities of subjects. Instead, in thermal comfort assessments the screening and observation methods given in ISO 8996 are predominantly used.

Humphreys and Nicol (2002) suggest that PMV is “free from serious bias” for activity levels below 1.4 MET. ASHRAE (2009) similarly states that its tabulated values are sufficiently accurate for well-defined activities with metabolic rates lower than 1.5 MET. Havenith et al. (2002), however, suggest obtaining more data and detailed task description for activities below 2 MET units to improve metabolic rate estimation based on ISO 8996. Moreover, apart from the problem with limited accuracy, tabulated values for various activities may not be applicable for “specific populations or individuals” (Parsons, 2001, Havenith et al., 2002).

Data and tabulated values for estimation of metabolic rate in the ISO standards (ISO 8996, 2004, ISO 7730, 2005) refer to an ‘average’ 30 year old adult (male 70kg, 1.8m^2 body surface area; female 60 kg, 1.6m^2 body surface area). Similarly, in (ASHRAE 55, 2010, ASHRAE, 2009) the metabolic rate is nominated for an average adult, with the skin surface area = 1.8 m^2 as estimated based by Du Bois and Du Bois (1916). Furthermore, the ISO standards estimate the metabolic rate of school activity as equal to office work, and require appropriate corrections when dealing with children (ISO 8996, 2004) because children’s body surface area and mass are lower than those of adults.

3. Physiological basis for determination of metabolic rate for children

3.1 Definition and origin of MET

A MET is generally defined as the rate of energy expenditure (EE) by a human at rest in thermoneutral conditions; however there are many different ways of quantifying it (Olds, personal communication, 23 August 2013). By definition, MET can be derived by the ratio of activity metabolic rate to the standard resting metabolic rate of 1 kcal (4.184 kJ)/kg/h, (Ainsworth et al., 1993) thus 1 MET corresponds to the resting metabolic rate when sitting quietly.

To describe the heat exchange of a man with the surrounding environment, Gagge et al. (1941) proposed a uniform practical unit mutually understandable among the three groups of heating engineers, physicians and the physiologists concerned with human heat exchange with the environment. The term ‘mets’ originated with Gagge et al. (1941) where a thermal activity unit is equivalent to 50kcal/h/m^2 or 18.5Btu/h.ft^2 based on the metabolism of a person sitting at rest in a thermal comfort state. As 1 ‘met’ unit is dependent on the size of individuals, for an average size person it is taken as equal to 100 W.

In work and exercise physiology, MET is usually determined by reference to the amount of oxygen consumption where 1 MET is approximately equivalent to resting oxygen intake of 3.5 ml/kg/min for an average adult (Ainsworth et al., 1993). A similar definition is given by Jette et al. (1990) in which a MET refers to the amount of oxygen consumed at rest when sitting quietly in a chair. The energy cost of an activity expressed in MET can be determined by the ratio of the relative oxygen cost of the activity (ml/kg/min) to 3.5. However, as pointed out in Harrell et al. (2005), the origin of the standard value defining 1 MET (3.5 ml/kg/min) is unclear.

It is given that resting oxygen consumption in children is somewhat more than this standard value (Olds, personal communication, 23 August 2013). It is also reported by Amorim (2007) that this value underestimates actual resting oxygen consumption and resting EE of children. A similar trend with children aged 8-18 years is highlighted in Harrell et al. (2005), where mean resting oxygen intake and adjusted resting EE are equivalent to 5.92 ml/kg/min and 1.71±0.41 kcal/kg/h respectively. Therefore, the application of standard resting oxygen consumption for children is not correct because the relationship between oxygen consumption and body size is not linear (Taylor, personal communication, 26 August 2013).

3.2 Basal and resting metabolic rate

Basal metabolic rate (BMR) as defined by McIntyre (1980, p. 87) is the minimum rate of energy production from the human body. It is often derived from measurement of oxygen consumption in a fully awake subject having fasted for 12 hours after resting quietly for 20-30 min in a thermoneutral condition prior to the measurement (Wong et al., 1996). Due to methodological difficulties in providing these standard conditions, an alternative 'resting metabolic rate' (RMR) is used which "requires an interval of only four hours following a light meal and a relatively short measurement time of between 30 to 60 minutes" (Amorim, 2007).

Basal metabolic rate differs in proportion to body surface area (Rhoades and Bell, 2013, p. 554) which is taken as proportional to the 2/3 power of body mass (IUPS Thermal Commission, 2001). However, Kleiber (1947) reviews the correlation between metabolic rate and body size based on zoology studies and concludes that BMR is more nearly proportional to the 3/4 power of body weight. The non-linear treatment is very important when dealing with children (Taylor, personal communication, 26 August 2013). Despite this, in many biological studies RMR value is expressed in terms of simple ratio scaling of body mass.

BMR is a function of several factors; including age and sex (McIntyre, 1980), stage of puberty (Harrell et al., 2005), body surface area, hormones, and digestion (Rhoades and Bell, 2013, p. 554). In a resting and fasting young adult man, who weighs 70 kg, and is 170 cm tall, body surface area (BSA) close to 1.8m^2, taking the usual oxygen equivalent of 1 MET (3.5 ml/kg/min) into account, BMR equates to 86W (3.5ml/kg/min × 70 kg = 0.245 l/min × 21 kJ/l = 5,145 J/min = 86 W→ 48 W/m^2) (Olds, personal communication, 23 August 2013). Rhoades and Bell (2013, p. 554) suggest a similar value for a young adult man of about 45 W/m^2.

Children's resting metabolic rate normalised for BSA is generally higher than the BSA-normalised values for adults (Olds, personal communication, 23 August 2013). Boothby et al. (1936) show that the basal metabolism per unit of body surface area expressed as calories per square meter per hour declines with age; being highest at age six for both sexes. According to the same study, the fall in basal metabolism is more rapid during early childhood and adolescence and slows thereafter into old age. Further, Holliday (1971) found that resting metabolic rate per kilogram body weight is higher in children compared to adults. Similarly, Harrell et al. (2005) concludes that "energy expenditure per kilogram of body mass at rest or during exercise is greater in children than adults and varies with pubertal status".

3.2.1 Estimation of RMR for children

Children's metabolic rate at rest has been reported variously in the literature, as studies vary in their methodological approaches. The review of previous studies by Amorim (2007) shows that RMR values vary from 1012 to 1420 and 1133 to 1358 (kcal/day) corresponding to lying and sitting positions respectively. Apart from difficulties imposed by the cost and availability of equipment, and measurement time (Finan et al., 1997), RMR measurement requires subjects' cooperation (Wong et al., 1996). Determining RMR in children under standardized conditions is considered "very tedious as it is imperative that children rest quietly over an extended period of time under the same conditions to gain reliable results" (Amorim, 2007). Therefore, several equations have been developed to predict RMR specifically for children.

The study by Schofield (1985) reviews 50 years of literature on basal metabolism and computes the widely used equations to predict RMR based on data obtained from a large heterogeneous sample from developed and underdeveloped countries from 1935 to 1985. These equations are used to simply predict RMR from weight (W) or from weight and height (WH) for different age groups and genders. The other frequently used equations are formulated by the Food and Agriculture/World Health Organization/United Nations University (FAO/WHO/UNU, 1985) to estimate BMR from body weight. These prediction equations are based on BMR values derived from worldwide measurements of resting energy expenditure (REE) in children and adolescents (Table 2).

Table 2. BMR prediction equations for children - W: weight (kg), H: height (m), F: female, M: male.

Author	**Equation for BMR** (MJ/24 h)	**R**
Schofield-W	M(3-10 yr): BMR= 0.095W+2.11	0.83
	F(3-10 yr): BMR= 0.085W+2.033	0.81
	M(10-18 yr): BMR= 0.074W+2.754	0.93
	F(10-18 yr): BMR= 0.056W+2.898	0.80
Schofield-WH	M(3-10 yr): BMR= 0.082W+0.545H+1.736	0.83
	F(3-10 yr): BMR= 0.071W+0.677H+1.553	0.81
	M(10-18 yr): BMR= 0.068W+0.574H+2.157	0.93
	F(10-18 yr): BMR= 0.035W+1.948H+0.837	0.82
FAO/WHO/UNU	M (3–10 yr): BMR= 0.0949W+2.07	0.86
	F (3–10 yr): BMR= 0.0941W+2.09	0.85
	M (10–18 yr): BMR= 0.0732W+2.72	0.90
	F(10–18 yr): BMR= 0.0510W+3.12	0.75

These equations has been validated in a number of studies (e.g. Rodriguez et al., 2002) where measurement are obtained in steady state thermoneutral condition on fully awake supine subjects.

3.3 Body surface area prediction equations

Body surface area is used in physiology to normalize metabolic rate of individuals of different body size. The correlation between body height, weight and surface area is given in different studies (e.g. Du Bois and Du Bois, 1916, Mosteller, 1987, Haycock et al., 1978) (Table 3). The formula provided by Du Bois and Du Bois (1916) has been widely used to estimate body surface area of subjects from height and weight. The Du Bois and Du Bois equation is validated with respect to adults and is not recommended to be applied in infants and young children (Haycock et al., 1978). The height and weight body surface area equation provided by Haycock et al. (1978) has been validated in infants, children, and adults with a wide range of samples varying in body shape and size. Children of different ethnicities were included in this study. The Mosteller formula (Mosteller, 1987) is also used for calculation of surface area. It is simpler than other formulas, and its deviation from values predicted by the Du Bois and Du Bois equation is less than 2% (Mosteller, 1987).

Table 3. Body surface area formula from body weight (W) and height (H)

Author	Year	Formulas
(Du Bois and Du Bois)	1916	A_{Du} (m^2) = 0.202 W (kg) $^{0.425}$× H (m) $^{0.725}$
(Haycock et al.)	1978	SA (m^2) = W (kg) $^{0.5378}$×H (cm) $^{0.3964}$×0.024265
(Mosteller)	1987	BSA(m^2) = [H (cm)×W (kg)/3600]$^{0.5}$

4. Review of previous thermal comfort studies in schools

The study by Havenith (2007) identified metabolic rate values corresponding to physical activity levels of 25 primary school children 9-11 years old, which were determined during different class activities using an indirect calorimeter (Table 4). The study shows that the metabolic rate of children during seated activities is lower than estimated metabolic rate for seated office work activities based on ISO Standards; i.e. 52 to 64 W/m^2 for 9-11 years old, and 62 and 64 W/m^2 for children 10-11 years old. The lower metabolic rate of school children per unit of surface area compared to estimated values in ISO 8996 (2004) was explained by their body size and the larger ratio of body surface area to mass (Havenith, 2007).

Table 4. Determination of metabolic rate for primary school children based on Havenith (2007)

Lesson	Sample size	Age	Description of activity (seated)	Metabolic rate-W	Metabolic rate-W/m^2
Language assignment	5	9-10	Working individually on worksheets	63	52
Writing task	5	9-10	Writing story	68	53
Art	5	9-10	Cutting and pasting with paper	77	59
Drawing	5	10-11	Seated activity	79	62
Calculus	5	10-11	Listening to teacher-follow book material	84	64

Children's metabolic heat production has been adjusted variously in a number of thermal comfort studies in schools to represent actual metabolic rate of children for calculation of PMV. A brief review of these approaches was presented in a previous paper (Haddad et al., 2013).

Children's metabolic rate in Al-Rashidi et al. (2009) was corrected based on the findings of Havenith (2007). However, both PMV and adjusted PMV under predict and over predict students' actual thermal sensation on the warm and cool side of neutral respectively, on the ASHRAE scale.

Mors et al. (2011) corrected mean metabolic rate for the reduced body surface area of children and found that the corresponding PMV underestimates children's thermal sensation. This investigation also showed that underestimation of PMV would be larger using children's actual metabolic rate based on Havenith (2007) than using body surface area corrected metabolism.

The recent study by Teli et al. (2012) applies four different adjustment approaches to address the metabolic rate of primary school children in naturally ventilated classrooms (table 5).

Table 5. Determination of metabolic rate for children based on (Teli et al., 2012). 1: Child RMR based on Amorim (2007) 2: Average activity metabolic rate base on Havenith (2007)

MET	RMR	Estimated values	PMV prediction
Estimated from children's RMR[1] and activity metabolic rate[2]	Unchanged	RMR=58.15W/m^2 MET=1.2	PMV underestimates TSV
Corrected for body surface area	Unchanged	RMR=58.15W/m^2 MET=1.8	PMV underestimates TSV
Corrected for body surface area	Corrected for body surface area	RMR=88.25W/m^2 MET=1.2	PMV overestimates TSV
Estimated from children's RMR[1] and activity metabolic rate[2]	Estimated from child RMR[1]	RMR[1]= 48.8W/m^2 MET=1.2	Large deviation between PMV and TSV

There is a poor agreement between previous thermal comfort studies in regards to estimation of metabolic rate for children. However, a more precise measure of metabolic rate is required for more accurate thermal comfort assessment (Van Hoof, 2008). To minimize uncertainty in metabolic rate estimation in the assessment of children's thermal comfort and examine the suitability of PMV for prediction of survey results, a sensitivity analysis was conducted and is reported in this paper, which sets a range of child-specific MET rates and RMR values in the PMV equation.

5. Methods

This study follows conventional techniques and protocols for data gathering commonly used in thermal comfort field surveys. For a detailed discussion of the questionnaire designed for the target age group see Haddad et al. (2012).

5.1 Subjects

Three campaigns of combined subjective and objective study were conducted with children aged 10-12 years in 58 classrooms located in seven nearby boys' and girls' primary schools in Shiraz, Iran. Data collection in this study was carried out in the warm and cool seasons of the school year (2012-2013) with about 1600 healthy subjects.

The subject school buildings were naturally ventilated using operable windows and equipped with mechanical cooling systems and water heating systems; i.e. evaporative coolers and radiators. Cooling systems were switched off during the survey period and heaters were occasionally operated in the cooler month.

Students' physical activity levels in the surveyed classrooms were effectively constant across all schools and for all seasons because the students had more or less the same posture and were involved in activities with similar duration and intensity during class−predominantly restricted to reading, writing, and listening to the teacher while seated for 45 minutes.

5.1.1 Body surface area

In a previous study, (Haddad et al., 2013) the body surface area of an average child of 10-12 years was derived from the literature, i.e. $1.14m^2$ in line with Mors et al. (2011) and Teli et al. (2012). For further refinement of likely accuracy, body weight and height of Shirazi school children were taken from the study by Ayatollahi and Bagheri (2010) as a baseline to estimate body surface area of an average child 10-12 years old. Children's BSA was predicted based on the three equations mentioned previously. Table 6 summarises the minor differences between calculated BSAs based on these formulas.

Table 6. Body surface area of Shirazi school children

BSA (m^2)			
Formula	Female	Male	Average
Du Bois and Du Bois (1916)	1.125	1.109	1.117
Haycock et al. (1978)	1.116	1.101	1.109
Mosteller (1987)	1.120	1.105	1.113

5.2 Study design

Several factors can lead to elevation in the estimated MET value: e.g. stressful activity (Fanger, 1994); performing mental tasks (Wyon et al., 1975); and the intensity, type, duration, and frequency of physical activity (Chen and Bassett, 2005). These are of importance in school settings where students mostly perform medium to vigorous activity during the breaks and may participate in stressful activities such as exams.

Further, the actual rate of energy expenditure in the classroom may be affected by three factors: 1) whether the children were active immediately before; 2) whether they have just eaten; and 3) the ambient temperature and relative humidity. Taylor (personal communication, June 21, 2013) also suggests that high-intensity and long-duration exercise results in a protracted elevation in resting metabolic rate.

In this study, children engaged in different activities during the 15 minute school break in which the intensities varied from light to high; i.e. sitting and relaxing 1.1 MET to playing in the school yard 6.3 MET as suggested in the *Compendium of Energy Expenditures for Youth* (Ridley et al., 2008). A study by Goto et al (2002) suggests that even short duration of activity could affect thermal sensations. The authors subsequently recommend that subjects need to maintain a stable level of activity for at least 15-20 minutes in order to have static thermal responses (Goto et al., 2006).

According to Toftum (personal communication, June 3, 2013) MET rate is expected to level off towards RMR; however it may not achieve this completely during 45 min. Accordingly, the thermal comfort survey was conducted during the last 5 min of the class session, to minimize the effects of any activities during the previous break.

5.2.1 Estimation of resting metabolic rate

In the authors' previous study (Haddad et al., 2013), three different RMR values were varied inside the PMV equation in line with Teli et al. (2012), mainly to enable comparison of PMV predictions between studies.

Given the difficulties in measurement of oxygen consumption particularly in a field study of thermal comfort with children, and methodological variability in the literature on measurement of RMR in children, this study employs Schofield's age-gender specific formulas (Schofield, 1985) to predict children's RMR. Schofield-W and Schofield-WH were derived from actual body height and weight of children for both male and female students (Table 7). Although Schofield-W and Schofield-WH suggested similar results, predictions of Schofield-WH were used, in accordance with the outcome of the study by Rodriguez et al. (2002) where RMR is a linear function of body weight and height.

For repeatability of the thermal comfort work, children's resting metabolic rates per unit of body surface area were calculated from RMR based on the Schofield-WH formula, divided by children's body surface area based on the Du Bois and Du Bois equation. Table 8 shows the derivation of RMR values normalized for body surface area based on three BSA formulas. Notewithstanding that there are minor differences between the values from the three BSA equations given in Table 8, the Du Bois and Du Bois BSA formula was used for normalizing metabolic rate, since it has been commonly used in the thermal comfort literature.

Table 7. Resting energy expenditure based on Schofield (1985)

Resting Energy Expenditure				
Gender-Age	BMR (MJ/24hr)		BMR (Watts)	
	Schofield-W	Schofield-WH	Schofield-W	Schofield-WH
Male (10-18 yr)	5.118	5.119	59.239	59.249
Female (10-18 yr)	4.721	4.679	54.638	54.156

It is noteworthy that basal and resting values can be similar, or can differ considerably (Taylor, personal communication, June, 21, 2013). That is because of the typical standardisation procedures that must be adhered to prior to basal reading for obtaining reliable measurements, as discussed in Section 3.2.

Since both meals and previous activity will increase metabolic rate, "it is likely that Schofield and similar equations will underestimate RMR if the child has recently eaten and/or has recently been active" (Olds, personal communication, December, 15, 2013).

Table 8. Resting metabolic rate normalized for body surface area

RMR (W/m^2)						
BSA formula	Schofield (1985)-W			Schofield (1985)-WH		
	Female	Male	Average	Female	Male	Average
(Du Bois and Du Bois)	48.55	53.39	50.97	48.12	53.40	50.76
(Haycock et al.)	48.96	53.80	51.38	48.53	53.81	51.17
(Mosteller)	48.78	53.61	51.19	48.35	53.62	50.98

5.2.2 Estimation of MET value

Different approaches have been presented to estimate the energy cost of activities for children. The review of published data by Ridley and Olds (2008) suggests that the magnitude of error is small "using adults METs, combined with child resting metabolic rates, as the best existing technique to assign EE to children when measured values are not available".

Torun (1989) indicates that when energy costs are expressed as a multiple of RMR, values are similar for boys and girls with no age-related differences in sedentary activities. For children under 15 years, lying down = 1.1 METs and sitting = 1.2 METs.

The youth compendium of energy expenditure developed by Ridley et al. (2008) provides a coding system on the energy cost of children and adolescents performing activities including school work based on the review of data undertaken by Ridley and Olds (2008). A MET value of 1.4 is assigned for the energy cost of activities entitled “sitting quietly” and “writing-sitting”, and 1.3 MET is assigned to “reading-sitting” (Ridley et al., 2008).

5.3 Calculation of PMV

Children’s mean thermal sensation votes (TSV) from 58 surveyed classrooms were then considered to investigate the PMV-TSV correlation. Physical variables including air temperature, globe temperature, air speed and relative humidity were collected concurrently during the surveys consistent with standards (ISO 7726, 2001, ASHRAE 55, 2010) from a Class 1 array of instruments placed at heights of 1.1m, 0.6m and 0.1m above the floor near the middle of each classroom.

PMV was calculated with a weighted average clo value. Two values were estimated for girls and boys depending on whether students wore jackets on top of their uniforms: 0.93, 0.65 for boys and 1.12, 0.84 for girls in the cold season and 0.86, 0.61 for boys and 1.02, 0.77 for girls during the warmer month. To calculate PMV-PPD according to the PMV equation (ISO 7730, 2005), the Basic code given in ASHRAE 55 (2010) was implemented in MATLAB computer software. This allows changing adults’ RMR (58.15 W/m^2) to the values corresponding to children for the purpose of sensitivity analysis.

6. Analysis and results

To understand PMV sensitivity relative to metabolic rate, PMV was calculated as a function of RMR and MET. As in (Haddad et al., 2013), MET values range from 1 to 1.4, and RMR= 58.15, 48.8, 88.25W/m^2. Additionally, in this study child-specific RMR was employed that was estimated based on the Schofield equations, i.e. 50.76 W/m^2.

Thermal neutrality was derived based on the mean thermal sensation vote as a function of operative temperature; $TSV_{(mean)}=0.23T_{op}-5.24$, $r^2= 0.757$. For each interval of MET and RMR value, one linear regression was generated to assess neutral temperature predicted by PMV and that governed by actual thermal sensation mean votes of the children. Figure 1 illustrates linear regression models derived from predicted PMVs and actual TSV versus operative temperature. The outcome of the regressions shows that PMV varies significantly with changes in RMR.

Taking all intervals of MET into account, RMR values corresponding to children result in discrepancies in predictions of PMVs: RMRs of 48.8 and 50.76 W/m^2 lead to underestimation of PMV. A similar trend is suggested where data obtained during cold and warm seasons are analysed separately; PMV with values measured or estimated for children underestimates mean TSV of the surveyed students. This result is consistent with observation made by Teli et al. (2012) where PMV with child-specific RMR and MET=1.2 underestimates children’s TSV, however, a larger deviation is observed in Teli et al. (2012).

In contrast with child-specific RMR, size corrected adult RMR, i.e. 88.25W/m^2 consistently falls above the regression line of actual thermal sensation of students. This indicates that correcting adults’ RMR for the smaller body surface area of children is not an appropriate approach because the relation with surface area is different for children (Havenith, personal communication, June 25, 2013).

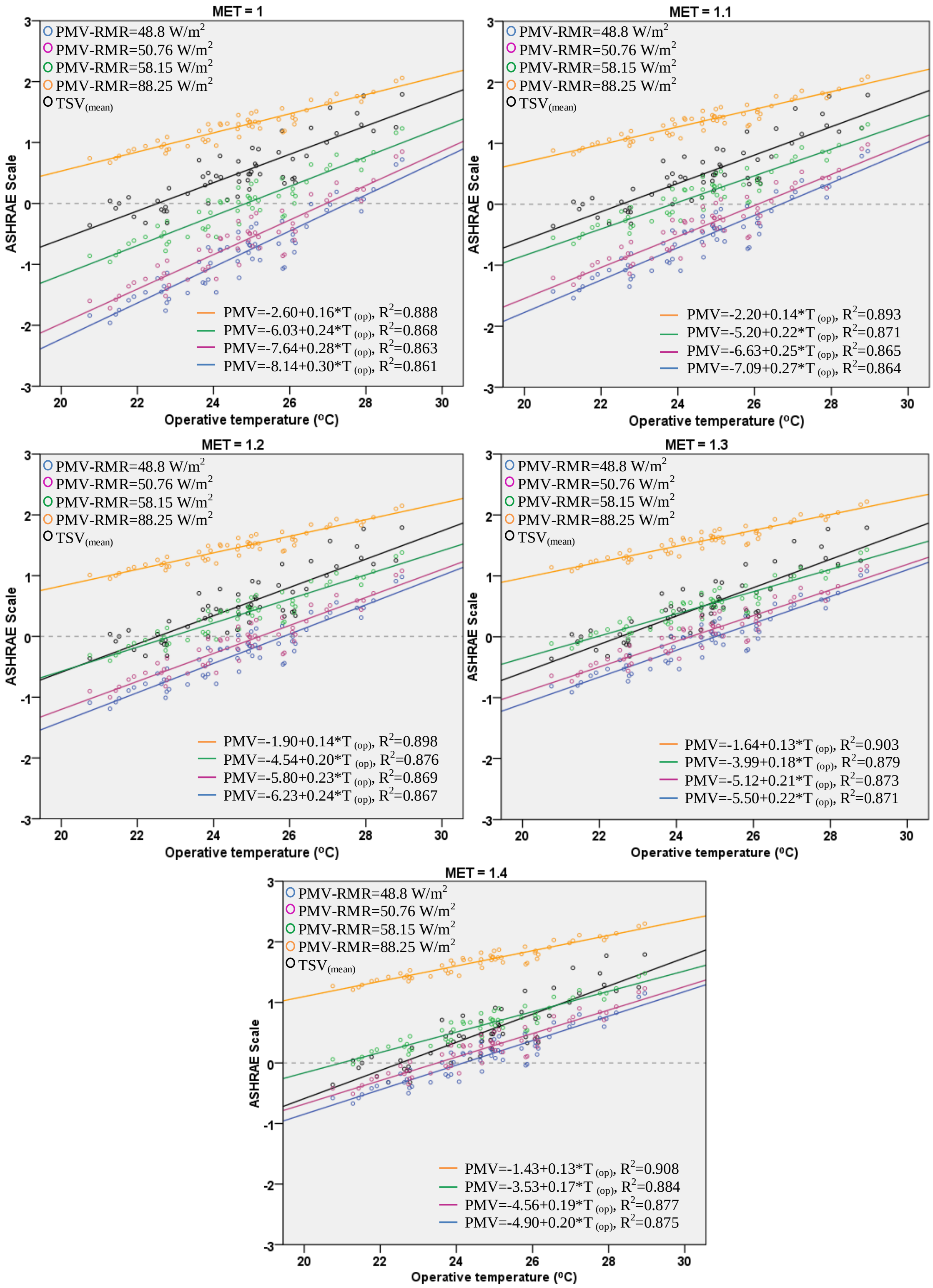

Figure 1. Linear regression calculation based on mean TSV and PMVs (vs.) operative temperature (^oC)

Regression analysis used to explore the relations between PMV and TSV shows a PMV regression line with child-specific RMR and MET=1.4 closer to the line representing the actual mean votes of the students, even though it slightly under-predicts TSV. To determine a metabolic rate for sedentary activity in the classroom, predicted RMR based on Schofield (1985) is multiplied by a MET value of 1.4 and 1.3 as given in Ridley et al. (2008) for seated class activity. The resulting values for the sample vary between 65.98 and 71.1 W/m^2 which is within the lower range of metabolic rates given in Nicol and Humphreys (1973) for classroom activities, 60-80W/m^2.

Analysis shows that the PMV fitted line slightly underestimates TSV where RMR was kept unchanged in the original PMV equation i.e. 58.15 W/m^2 and MET=1.2 for sedentary school activity. This could be explained by less opportunity for adaptive behaviour in the classroom or greater sensitivity of children to higher temperature.

For the purpose of sensitivity analysis, in this study loss function analysis was employed using Eq.1 in order to define a combination of MET and RMR such that PMV predictions are close to children's TSV $_{(mean)}$. In this equation, the "j" indices correspond to number of classrooms where J=58 and the "i" indices refer to each (RMR, MET) combination. A lower value of L_i indicates that the PMV model is showing results that are closer to reality (TSV).

Eq.1. Loss function equation to find (RMR, MET)

$$L_i = \sqrt{\frac{1}{j}\sum_{j=1}^{J}\left(TSV_{(mean)} - PMV_j\right)^2}$$

A contour plot was derived to illustrate the effects of different RMR and MET combinations and the resulting L_i factors (figure 2). The dark blue area represents the combination of RMRs and METs that give the lowest L_i. The middle of this area can be captured as representing the combination of RMR and MET values with minimum discrepancy between PMV and actual votes of students. Among intervals of MET and RMR used in the sensitivity analysis, the lowest L_i of 0.26 was suggested by RMR=58.15 W/m^2 and MET=1.3.

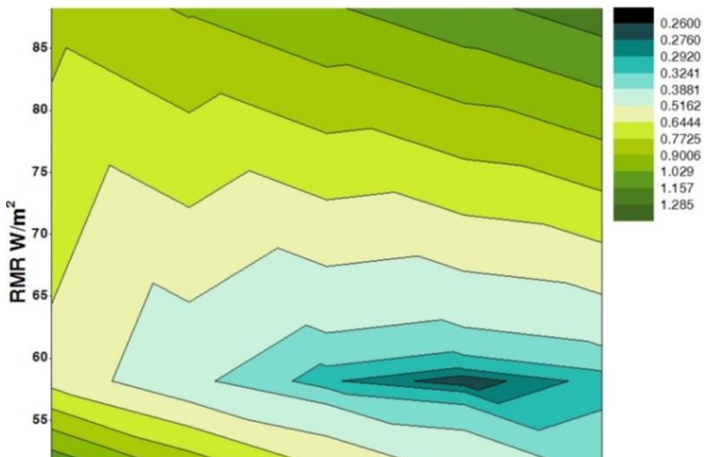

Figure 2. Contour plot for all combination of MET and RMR

7. Discussion

The use of either BMR calculated from the Schofield equation (50.76 W/m^2) or RMR as commonly applied in adult thermal comfort studies (58.15 W/m^2) to predict PMV contributes to internal uncertainty in comparing children's TSV with that of adults. Apart from assumptions of metabolic rate, a systematic uncertainty in the calculation of PMV may be introduced by: 1) sensitivity of PMV to other variables, essentially estimation of clothing and chair insulation 2) other physiological variables and assumptions, e.g. mean skin temperature and sweat secretion which are given as a function of metabolic rate in the PMV equation.

In this study thermal insulation provided by wooden chairs used in the classrooms is estimated in line with standards (ASHRAE 55, 2010, ISO 7730, 2005) i.e. I_{clu}= 0.01 and added to the entire clothing ensembles. However, several factors influence chair insulation; e.g. contact area between the body and chair, posture, and type of chair, (McCullough et al., 1994). Therefore, estimation of additional insulation provided by chairs may contribute to the uncertainty in the PMV predictions.

Skin temperatures and sweat rates are the only physiological parameters which affect heat balance and that depend on activity level (Fanger, 1970, p. 21). Since these values vary with activity and individuals (Olesen, 1982), there is a need for more in-depth research into the physiological comfort conditions and implication of skin temperature and sweat secretion in the heat balance equation for children.

Compared with adults, children have a higher surface area to mass ratio (Parsons, 2003, p. 147, Bar-Or, 1989, p. 337). Therefore, the rate of heat exchange between the environment and body is higher in children than adults (Parsons, 2003, p. 147). Notwithstanding that geometric and physiological characteristics of children are different from those of adults, according to Bar-Or (1989, p. 354) “children seem to be as effective thermoregulators as adults in ambient conditions that are neither very hot nor very cold”. However, in terms of temperature regulation, Bar-Or (1989) concludes that “compared with adults, children dissipate heat less through evaporation and more through convection plus radiation, which is achieved by greater vasodilation”. Further discussion is beyond the scope of this field study since children were not involved in high intensity activity and not exposed to extreme environmental conditions in the classroom.

8. Conclusion

The validity of PMV predictions in relation to assumptions of metabolic rate were examined based on data collected from field work in non-air conditioned primary schools in Shiraz, Iran. This study employs intervals of MET rates and RMRs to assess the suitability of adjustment approaches in the calculation of PMV, and understand the effects of children’s metabolic rate on PMV predictions. The outcome of this study highlights the importance of metabolic rate in the prediction of PMV.

The first conclusion is that PMV is sensitive to RMR. Changing RMR values for children at neutral temperature leads to deviations from actual neutral votes which might have different explanations. The most likely explanation is that the PMV model was developed under laboratory conditions on the basis of adults’ physiology and any change in this equation may result in over or underestimation of actual thermal sensation of children. PMV predictions with child-specific RMR underestimate TSV of sample children which can be explained by issues with methodology.

Several factors can lead to elevation of resting metabolism from basal level, e.g. higher rate of activity during school breaks. Therefore, it seems reasonable to assume that children’s actual RMR during quiet sitting in the classroom would be higher than values obtained from estimated or measured BMR derived under ideal conditions. Measurement of metabolic rate during resting state and class activities would eliminate uncertainty in predictions of the comfort equation for children. However, this is hardly practical in a field study of thermal comfort.

The analysis also suggests that PMV predictions based on the original RMR in Fanger's PMV equation (58.15W/m^2) and MET = 1.3, are more robust compared to other values estimated or adjusted specifically for children. However, the literature predominantly indicates that children's resting metabolic rate per unit of body size is higher than that of adults, whereas published data for children (either estimated or measured) suggests lower values than the RMR value of 58.15W/m^2 used in the heat balance for adults. Therefore acknowledging the important role of metabolic rate estimation in assessment of thermal comfort, it would be desirable to obtain actual field measurements of subjects' RMR using calorimeters and reconsider its implication in the PMV equation in order to attain more confidence in this conclusion.

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