Fanger's Thermal Comfort and Draught Models

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Executive Summary

In this review, we assessed the validity of two commonly used thermal comfort models. The first, Fanger's Predicted Mean Vote (PMV) Model, combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people. The second, Fanger's Draught Model, predicts the percentage of occupants dissatisfied with local draught, from three physical variables (air temperature, mean air velocity, and turbulence intensity).

Our review indicated that the PMV model is not always a good predictor of actual thermal sensation, particularly in field study settings. Discrepancies between actual and predicted thermal sensations reflect, in part, the difficulties inherent in obtaining accurate measures of clothing insulation and activity level. In most practical settings, poor estimations of these two variables are likely to reduce the accuracy of PMV predictions. Our review also suggested that the bias in PMV predictions varies by context. The model was a better predictor in air-conditioned buildings than naturally ventilated ones, in part because of the influence of outdoor temperature, and opportunities for adaptation.

Although biases occur, the thermal conditions typically found in North American air-conditioned office buildings are unlikely to fall in the ranges associated with the most serious bias in PMV predictions. Within the context of the COPE project, it is important to be aware of the limitations of Fanger's PMV model. This acknowledged, it is fair to conclude that Fanger's PMV model can be applied within the COPE project, and will produce reasonably accurate predictions of occupant thermal sensation.

In comparison to Fanger's PMV model, much less work has focused on the validity of Fanger's Draught Model. Our review highlighted a number of methodological and contextual limitations that might undermine the accuracy of the model's predictions. Among the most interesting were recent studies that suggested that air movement might be perceived as pleasant, rather than unwanted discomfort, at higher air temperatures. There was also evidence to suggest that occupants were more tolerant of draughts if they had personal control over air delivery devices.

Based on the available evidence, we found no reason to suggest that predictions based on Fanger's draught model would be seriously biased, provided that it's original assumptions were met. More specifically, for occupants wearing normal indoor clothing, performing sedentary activities, at or near whole body thermal comfort, and without personal control over air velocity, Fanger's draught model can reasonably be applied without concern for serious bias.

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1.0 Introduction

The main reason for mechanically conditioning office buildings is to create comfortable thermal conditions for occupants (ASHRAE, 1992; 2001; Brager, Fountain, Benton, Arens & Bauman, 1994; Schiller, 1990). Studies of occupant satisfaction often identify temperature as one of the most important aspects of the office environment, and a factor that frequently receives complaints (e.g. Brill, Margulis, Konar & BOSTI, 1984; Louis Harris & Associates, 1980). As climate control is one of the largest sources of energy use in buildings, it is important to balance energy savings against occupant needs. However, *"although modifying the conditions at which we maintain the indoor thermal environment may result in both energy and cost savings, it is not always clear how deviations from optimum thermal conditions may affect the occupant's comfort…"* (Schiller, 1990, p.609).

To determine appropriate thermal conditions, practitioners refer to standards such as ASHRAE *Standard 55* (ASHRAE, 1992) and ISO *Standard 7730* (ISO, 1994). These standards define temperature ranges that should result in thermal satisfaction for at least 80% of occupants in a space. The standards are based primarily on mathematical models, developed by Fanger and colleagues on the basis of laboratory studies (see Fanger, 1970). In particular, these researchers developed a model of whole body thermal comfort, known as the Predicted Mean Vote (PMV) model (Fanger, 1970), and a model of local discomfort from draught (Fanger, Melikov, Hanzawa & Ring, 1988)[1].

Although Fanger's PMV and draught models have become the standard method of predicting thermal comfort for occupants, some researchers question their validity. Within the context of the COPE project, it is important to be aware of any limitations in these models, before they are applied in experimental or field study analyses. Therefore, in this report we reviewed the available literature on the PMV and draught models, to assess their ability to accurately predict thermal comfort.

Literature for this review was selected primarily from the COPEINFO database. This database was created as part of the COPE project and currently contains over 1,000 records. The database is the result of detailed searches performed on a number of engineering, science, medical, psychological and human factors electronic literature databases, such as *EI Compendex, INSPEC, Current Contents, Ergonomic Abstracts, PsychInfo* and *Medline*. The resulting database includes literature from journals such as *Indoor Air, ASHRAE Transactions, Energy and Buildings, Journal of Environmental Psychology, Journal of Occupational Medicine* and *Environment International*. The database also includes records from conferences such as *Indoor Air, IAQ, CLIMA 2000, Thermal Comfort: Past and Present,* and the *Human Factors and*

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[1] Feeling draught at the head or ankles is one cause of local thermal discomfort. Local discomfort can also arise from differences in temperature between the head and ankles, cold floor surfaces, and asymmetric radiation from cold/warm windows, surfaces or ceilings. In this review, only local discomfort from draught is discussed. For further information on other sources of local discomfort, refer to ASHRAE *Standard 55* (ASHRAE, 1992).

Ergonomics Society, in addition to a number of books, book chapters and reports. In order to maintain relevance, new searches are regularly performed and recently published material added to the COPEINFO database. Thus, the COPEINFO database provides detailed information of recent research, from which to select articles relevant to the current literature review.

For this review, we selected literature that addressed Fanger's PMV and draught models. Comparisons with other models of thermal comfort (e.g. Gagge, Foblets & Berglund, 1986) were not included. The majority of selected literature focused on office environments, although other settings were also considered where appropriate. Most of the selected papers were published between 1980 and 2002. However, some older papers, particularly those that document Fanger's original research, were also included. The resulting literature included both laboratory and field studies, in addition to review articles and theoretical discussions.

2.0 Fanger's PMV Model

Fanger's Predicted Mean Vote (PMV) model was developed in the 1970's from laboratory and climate chamber studies. In these studies, participants were dressed in standardised clothing and completed standardised activities, while exposed to different thermal environments. In some studies the researchers chose the thermal conditions, and participants recorded how hot or cold they felt, using the seven-point ASHRAE thermal sensation scale shown in Figure 1. In other studies, participants controlled the thermal environment themselves, adjusting the temperature until they felt thermally 'neutral' (i.e. neither hot nor cold; equivalent to voting '0' on the ASHRAE thermal sensation scale).

The PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity) and two personal variables (clothing insulation and activity level) into an index that can be used to predict thermal comfort. The index provides a score that corresponds to the ASHRAE thermal sensation scale, and represents the average thermal sensation felt by a large group of people in a space (ASHRAE, 2001; Fanger, 1970).

Figure 1: ASHRAE Thermal Sensation Scale

-3	-2	-1	0	1	2	3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

2.1 Derivation of Fanger's PMV Model

Fanger's PMV model is based on thermoregulation and heat balance theories. According to these theories, the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body. In extreme thermal conditions, this regulation is necessary for the body to function properly. In office buildings, it is very unlikely that temperatures associated with serious bodily dysfunction will occur, but thermoregulation is still used to maintain a comfortable heat balance (ASHRAE, 2001).

Maintaining this heat balance is the first condition for achieving a neutral thermal sensation. However, Fanger (1970) noted that *"man's thermoregulatory system is quite effective* *and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist"* (p.21). To be able to predict conditions where thermal neutrality would occur, Fanger (1967) investigated the body's physiological processes when it is close to neutral. Fanger determined that the only physiological processes influencing heat balance in this context were sweat rate and mean skin temperature, and that these processes were a function of activity level.

Fanger (1967) used data from a study by McNall, Jaax, Rohles, Nevins and Springer (1967) to derive a linear relationship between activity level and sweat rate. College-age participants in this study were exposed to different thermal conditions while wearing standardised clothing, and voted on their thermal sensation, using the ASHRAE scale. The linear relationship was formed from those participants (n=183) who stated that they felt thermally neutral (i.e. voted '0') for a given activity level.

Fanger (1967) also conducted a study using 20 college-age participants, to derive a linear relationship between activity level and mean skin temperature. In this experiment, participants wore standardised clothing and took part in climate chamber tests at four different activity levels (sedentary, low, medium and high). It is important to note that participants were not asked to vote on their thermal sensation in this study. Instead, the experimental conditions used temperatures that had been found to achieve thermal neutrality in McNall et al's (1967) study. Therefore, although Fanger claimed that the participants were at, or near, thermal neutrality, this assumption was not directly tested. This methodology has lead some to question the formulation of the PMV model.

Fanger (1967) substituted these two linear relationships into heat balance equations, to create a 'comfort equation'. The comfort equation describes all combinations of the six PMV input variables that result in a neutral thermal sensation. This equation was then validated against studies by Nevins, Rohles, Springer and Feyerherm (1966) and McNall et al (1967), in which college-age participants rated their thermal sensation in response to specified thermal environments. The air temperature where participants were thermally neutral in these studies showed good agreement with the predictions made by the comfort equation.

The comfort equation predicts conditions where occupants will feel thermally neutral. However, for practical applications, it is also important to consider situations where subjects do not feel neutral. By combining data from Nevins et al (1966), McNall et al (1967) and his own studies, Fanger (1970) used data from 1396 participants to expand the comfort equation. The resulting equation described thermal comfort as the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e. neutral) comfort for a given activity. This expanded equation related thermal conditions to the seven-point ASHRAE thermal sensation scale, and became known as the PMV index.

Fanger (1970) also developed a related index, called the Predicted Percentage Dissatisfied (PPD). This index is calculated from PMV, and predicts the percentage of people who are likely to be dissatisfied with a given thermal environment. The PMV and PPD form a U-shaped relationship, where percentage dissatisfied increases for PMV values above and below zero (thermally neutral).

The PMV index is mathematically complex to compute, so Fanger (1970) provided look-up tables to help practitioners determine appropriate thermal conditions. Information from these tables, and graphical representations of comfort conditions, is also provided in modern thermal comfort standards (e.g. ASHRAE, 1992: ISO, 1994). In recent years, computer programs have been developed to calculate PMV, and programming code is provided in ISO *Standard 7730* (ISO, 1994).

Thermal comfort standards use the PMV model to recommend acceptable thermal comfort conditions. The recommendations made by ASHRAE *Standard 55* (ASHRAE, 1992) are shown in Figure 2. These thermal conditions should ensure that at least 90% of occupants feel thermally satisfied[2].

Figure 2: Thermal Comfort Conditions - ASHRAE *Standard 55* (1992)

Season	Optimum Temperature[a]	Acceptable Temperature Range[a]	Assumptions for other PMV inputs[b]
winter	22°C	20-23°C	relative humidity: 50% mean relative velocity: < 0.15 m/s mean radiant temperature: equal to air temperature metabolic rate: 1.2 met clothing insulation: 0.9 clo
summer	24.5°C	23-26°C	relative humidity: 50% mean relative velocity: < 0.15 m/s mean radiant temperature: equal to air temperature metabolic rate: 1.2 met clothing insulation: 0.5 clo

a: refers to operative temperature, defined as *"the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. Operative temperature* [t_o] *is numerically the average of the air temperature* (t_a) *and mean radiant temperature* ($\bar{t}_r$)*, weighted by their respective heat transfer coefficients* (h_c *and* h_r)*:* (ASHRAE *Standard 55*, 1992, p.4)

$$t_o = (h_c t_a + h_r \bar{t}_r)/(h_c + h_r) \text{ ''}$$

b: if the value of these assumptions differs, refer to comfort zone diagrams and tables given in ASHRAE *Standard 55*, for appropriate temperature ranges.

2.2 Theoretical Considerations

Before assessing the validity of the PMV model, it is important to note some theoretical considerations with respect to its use.

Firstly, the PMV model is designed to predict the average thermal sensation for a large group of people. Within such a group, optimal thermal conditions are likely to vary between individuals by up to 1.15°C (Fanger & Langkilde, 1975), or up to 1 scale unit of the ASHRAE thermal sensation scale (Humphreys & Nicol, 2002). Therefore, even if the thermal environment in a space is maintained in accordance with the PMV model, there will be some occupants who are thermally uncomfortable. These differences between people are acknowledged by Fanger (1970), and are also reflected in the PPD index. At the neutral temperature as defined by the PMV index, PPD indicates that 5% of occupants will still be dissatisfied with the thermal environment. The difficulty in achieving thermal neutrality for all occupants in a space is also reflected in the percentage dissatisfied targets (typically 90% for whole body comfort) set by

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[2] The overall goal of this standard is to ensure that 80% or more occupants will be satisfied with the thermal environment. Conditions for whole-body comfort are set at 90%, to allow for an additional 10% dissatisfaction from local thermal conditions.

thermal comfort standards. Therefore, while the PMV model can be used to determine appropriate temperatures that will satisfy the majority of occupants, it is unrealistic to expect all occupants to be thermally satisfied.

Secondly, it is important to remember that the PMV model is based on a measure of how warm or cool occupants feel. Conceptually, however, thermal sensation is different from measures such as thermal satisfaction (e.g. I am satisfied/ unsatisfied with the thermal conditions), thermal acceptability (e.g. the thermal conditions are acceptable/ unacceptable), thermal comfort (e.g. I feel comfortable/ uncomfortable), and thermal preference (e.g. I would like to be warmer/ cooler). Thermal sensation simply measures the temperature that occupants perceive, whereas other measures also ask occupants to evaluate the appropriateness of that temperature. ASHRAE thermal sensation values of –1, 0, and +1 are typically assumed to represent "satisfaction", but direct measures of thermal satisfaction do not form part of the PMV model.

While it is likely that there will be overlap between occupants' responses on the above measures, findings from a number of researchers suggest that these concepts are not identical. Paciuk and Becker (2002), for example, found that of those naturally-ventilated home residents voting ±1 on the thermal sensation scale, almost half also reported that they were not comfortable (on a five-point thermal comfort scale). In addition, although most residents of air-conditioned homes voted that they were comfortable, their thermal sensation responses ranged from –3 to +1. Similarly, Schiller (1990) found that 27-39% of office occupants who voted in the extreme categories of the thermal sensation scale (i.e. -3, -2, +2, +3) also reported that they were moderately or very comfortable (on a six-point thermal comfort scale). In a study by Brager et al (1994), it was found that 11-36% of office occupants voting 0 (i.e. neutral) on the thermal sensation scale also reported that they would prefer to feel warmer or cooler (on a three-point thermal preference scale). These researchers also found that, of those occupants who reported more extreme thermal sensations (i.e. -3, -2, +2, +3), 3-50% also preferred no change in temperature, and 3-66% reported they were comfortable (on a six-point thermal comfort scale). Overall, these findings suggest that thermal sensation cannot be assumed to be equivalent to other, evaluative, measures of thermal comfort.

These theoretical considerations do not invalidate the PMV model, in and of themselves. Rather, they serve as limitations on the application and interpretation of the PMV model.

2.3 Predictive Ability of the PMV Model

Since the PMV model was developed, a large number of thermal comfort studies have been conducted (e.g. Auliciems, 1977; Auliciems & de Dear, 1986; Baillie, Griffiths & Huber, 1987; Brager et al, 1994; Busch, 1990; Busch, 1992; Cena & de Dear 2001; Cena, Spotila & Avery, 1986; Cena, Spotila & Ryan, 1988; Croome, Gan & Abwi, 1992; de Dear & Auliciems, 1985; de Dear & Fountain, 1994; de Dear, Fountain, Popovic, Watkins, Brager, Arens, et al, 1993; de Dear, Leow & Ameen, 1991; de Dear, Leow & Foo, 1991; Donninni, Molina, Martello, Lai, Change, Laflamme, Nguyen & Haghighat, 1996; Feriadi, Wong, Chandra, Cheong & Tham, 2002; Fishman & Pimbert, 1979; Griffiths, 1990; Grivel & Barth, 1980; Howell & Kennedy, 1979; Howell & Stramler, 1981; Humphreys & Nicol, 1990; Jitkhajornwanich & Pitts, 2002; Jones, 2002; Morgan, de Dear & Brager, 2002; Newsham & Tiller, 1995; Nicol & Humphreys, 2002; Oseland & Raw, 1990; Oseland, 1996; Rowe, 2001; Schiller, 1990; Schiller, Arens, Bauman, Benton, Fountain & Doherty, 1988; Tsuzuki & Ohfuku, 2002; Williamson, Coldicutt & Penny, 1989; Zhu, Liu & Tian, 2002). In many of these studies, researchers have compared the neutral thermal sensation, and associated neutral temperature, predicted by the PMV model, against that given by an actual group of participants (the actual mean vote (AMV)) voting on the

ASHRAE thermal sensation scale.

In general, early laboratory studies compared well with the PMV index (Humphreys, 1994). However, more recent laboratory studies have shown greater discrepancies from predicted neutral temperatures. In a review of laboratory studies, Doherty and Arens (1988) concluded that there were discrepancies between predicted and actual thermal sensation as large as 1.3 scale units. Similarly, in a review by Humphreys (1994), the observed neutral temperatures in eight climate chamber studies conducted since the 1980's, were found to be between 0.8°C lower and 3°C higher than those predicted by the PMV. Humphreys (1994) also noted that the PMV model was most accurate in laboratory studies that used sedentary activities and light clothing, but that the discrepancy between PMV and actual mean vote increased for heavier clothing and higher activity levels.

For field studies of thermal comfort, Oseland (1995) noted that *"since the development of the PMV equation many field studies have shown differences between the occupants' reported TS* [thermal sensation] *and those predicted by PMV and the corresponding neutral temperatures"* (p.105). Schiller (1990), for example, found that PMV predicted a neutral temperature 2.4°C higher than that given from actual thermal sensation votes, in a sample of San Francisco office workers. Similarly, Oseland's (1996) study of British office buildings found that PMV over-predicted actual neutral temperature by up to 3.6°C. Field studies by de Dear and Auliciems (1985), in Australian offices, also show an over-prediction of actual neutral temperature, by up to 2.2°C.

Several researchers have reviewed the literature on thermal comfort field studies. Humphreys (1975), for example, reviewed 30 studies, and found that PMV generally over-predicted actual neutral temperature. Later reviews by Humphreys (1976; 1978) reached similar conclusions, as did Auliciems' (1981) review of 53 studies. More recent reviews have found both under- and over- predictions of the actual mean vote of occupants. Humphreys (1994) for example, found discrepancies in both directions, with an average difference of 3°C between predicted and actual neutral temperatures. Brager and de Dear (1998) reviewed 18 field studies, and found that PMV overestimated actual neutral temperature by up to 2.1°C and underestimated it by up to 3.4°C. This more recent trend towards both over- and under- predictions might reflect the wider range of countries and climates in which thermal comfort studies have now been conducted. Oseland and Humphreys (1994) concluded that *"the use of PMV encourages unnecessary heating in cool conditions and unnecessary cooling in warm conditions"* (p.36).

In addition to differences between actual and predicted neutral temperatures, several field studies have suggested that occupants' sensitivity to changes in temperature differ from those predicted from PMV. For example, de Dear et al (1993) found that, although observed neutral temperatures were largely consistent with those predicted by PMV, predicted and actual thermal sensation differed for non-neutral conditions, and got larger the further away from neutrality occupants were. These findings suggested that occupants were more sensitive to changes in temperature than the PMV model would predict. A number of other studies also support this conclusion (e.g. Busch, 1992; Croome et al, 1992; Oseland, 1995; Schiller, 1990).

In an attempt to study these discrepancies more systematically, ASHRAE commissioned the formation of a large database of thermal comfort studies (see de Dear, 1998). The database, part of ASHRAE research project RP-884, is the result of a series of high-quality thermal comfort field studies conducted in different climates around the world. To be included, studies had to carefully measure the six PMV input variables and the thermal sensation of actual occupants, using a standardised procedure. The database contains raw data from these studies, which means that the whole database can be subjected to the same analyses. This reduces the variability of findings that might be influenced by different statistical approaches between studies (Humphreys

& Nicol, 2002; Jones, 2002). Data on 22,346 participants from 160 buildings were collected, and include data from four continents, with countries as diverse as Thailand, UK, Indonesia, USA, Canada, Greece, Pakistan, and Singapore being represented. This database has been subjected to analysis by number of researchers (e.g. de Dear & Brager, 1998; 2001; 2002; Humphreys & Nicol, 2000; 2002), and these analyses will be referred to throughout this review.

Humphreys and Nicol (2002) compared predicted and actual thermal sensation votes using the ASHRAE RP-884 database. When the database was analysed as a whole, these researchers found that the PMV was a valid index, and predicted thermal sensation within 0.11 ±0.01 scale units of the observed votes. However, when analyses were conducted on each separate sample in the database, 33 out of 41 samples showed evidence of PMV bias. In the majority of these cases, PMV deviated from actual thermal sensation by more than ±0.25 scale units (i.e. more than would be reasonably expected from random error), and some differed by as much as ±1.0 scale unit. These researchers also found that the discrepancies became larger, as thermal conditions moved further away from neutral.

Overall, thermal comfort studies suggest that the PMV model does not always accurately predict the actual thermal sensation of occupants, particularly in field settings. Two factors are commonly cited as contributing to the discrepancies described above: measurement error, and contextual assumptions. These two factors are discussed below.

3.0 Measurement Error

The PMV model is based on climate chamber experiments, during which the four physical variables (air temperature, mean radiant temperature, relative humidity, and air velocity) can be closely controlled and monitored. The use of standardised clothing and activities ensures that clothing insulation and activity level can also be accurately quantified. In field settings, it is more difficult to control or to accurately measure these six variables. Measurement error resulting from these difficulties has been argued to contribute to the discrepancies found between PMV and actual thermal sensation (Benton, Bauman & Fountain, 1990; de Dear & Brager, 1998; 2002, Fanger, 1994; Oseland, 1994). As noted by Fanger (1994), *"to make a fair comparison, it is essential that all four environmental factors are properly measured and that a careful estimation is made of the activity and clothing. Poor input data will provide a poor prediction"* (p.12).

3.1 Physical Variables

The reliability of the four physical inputs to the PMV model depends on the instruments used to collect the data, and the measurement strategy adopted. Early thermal instruments had wider ranges of error than those available today, particularly those for measuring air velocity (Benton et al, 1990). However, it is generally accepted that modern thermal sensors are adequately accurate, especially if they are selected and used in accordance with guidelines provided by professional organisations (e.g. ASHRAE, 1992; 2001; ISO, 1994).

Prior to the mid 1980's, studies tended to use relatively simple measurement protocols, often relying on a single set of thermal sensors in one location (Benton et al, 1990; Humphreys, 1994). This increased the probability that the physical conditions measured were not representative of the whole space. More recent studies are more sophisticated and rigorous in their measurement strategies. These studies typically use repeated measurements in a large, representative sample of locations, and are guided by standardised procedures developed by professional organisations. The studies that form the ASHRAE RP-884 database were all conducted using a common methodology, to increase ease of comparability, and to reduce variability in measurement error.

Therefore, although some measurement error in physical variables is likely to be present in PMV calculations, it is unlikely that they seriously compromise the validity of the PMV model.

3.2 Clothing Insulation

Clothing insulation is measured in units of 'clo' (Gagge, Burton & Bazett, 1941). Establishing the insulating properties of clothing is a time-consuming and detailed process, that is usually conducted in laboratory experiments devoted to this purpose. As it is not practical to directly measure clothing insulation in most thermal comfort studies, researchers generally estimate these values, using tables that have been developed from clothing insulation studies (see ASHRAE, 1992; ISO, 1994; 1995). Some researchers assume an average clo value for all occupants, based on the season and climate of the study location, and typical clothing ensembles for office work (typically 0.35-0.6 clo in summer, and 0.8-1.2 clo in winter). More detailed studies ask occupants to complete a garment checklist, which can then be used to select a more appropriate clo value for the group, or separate clo values for each participant.

Clothing insulation tables are constructed from laboratory studies, usually using thermal manikins in conditions of still air. As such, it still remains unclear how clothing insulation might differ in field settings. Oseland and Humphreys (1994) noted that clo studies show good agreement between thermal manikins and humans during sedentary activities, but that their correspondence decreases for other activity levels. Studies using thermal manikins have suggested that body movement has a minimal effect on clo values (Olesen & Nielsen, 1984; Olesen, Sliwinski, Madsen & Fanger, 1982), while studies using humans suggested that there are effects (Berger, 1988; Chang, Arens & Gonzalez, 1988; Vogt, Meyer, Sagot & Candas, 1984). Havenith, Holmer and Parsons (2002) concluded that body and air movement do affect clothing insulation, and that *"…using the static values given in ISO 9920 for climate assessment will imply an overestimation of the actual insulation, and real heat loss will be bigger than suggested by these values"* (p.582). In addition, although knowledge in this area is expanding, current clo values are relatively simple, and do not fully reflect the effects of posture, clothing material and cut, dynamic heat transfer, or variations in heat loss over the body (Cena, 1994; Havenith et al, 2002; Humphreys, 1994; Olesen & Parsons, 2002; Oseland & Humphreys, 1994; Wyon, 1994).

One factor that was not accounted for in earlier thermal comfort studies was the insulating properties of an occupant's chair. Climate chamber studies have suggested that clo estimates should be increased by 0.15 clo, to account for chair insulation (Tanabe, 1992, cited in Brager et al, 1994), and some researchers argue for increases up to 0.3 clo, depending on the type of chair (Fanger, 1992).

Using detailed garment checklists, up-to-date clothing insulation tables, and accounting for chair insulation can, therefore, improve thermal comfort researchers' estimations of clo values. Brager et al (1994), for example, reanalysed their data from San Francisco office buildings, after increasing clo to account for chair insulation (+0.15 clo) and the most recent clo value tables (average +0.1 clo). These adjustments improved the correspondence between PMV and actual thermal sensation votes. However, even with such adjustments, the clo values used in thermal comfort studies are still based on estimation. In addition, clo estimates do not accurately reflect differences between people, changes in clothing during the day, or social and contextual constraints on clothing choices (de Dear & Brager, 2002; Humphreys, 1994; Oseland & Humphreys, 1994). Taken together, clo values present a source of concern for PMV calculations, and are likely to contribute to discrepancies between predicted and actual thermal sensation.

Humphreys and Nicol's (2002) analysis of the ASHRAE RP-884 database found that the accuracy of PMV predictions varied, depending on clo value. PMV best predicted actual neutral temperatures for clothing insulation (including chair) in the range of 0.3 to 1.2 clo. For heavier and lighter clothing, PMV tended to overestimate actual neutral temperatures.

3.3 Activity Level

Activity level is measured in terms of metabolic rate, or 'met' (Gagge et al, 1941). The most accurate method for determining met is through laboratory studies, where heat or oxygen production are measured for participants conducting specific activities (Havenith et al, 2002; Olesen & Parsons, 2002). Alternatively, the participant's heart rate can be measured and compared to previously developed tables of heart rate for specific activities. All of these methods, however, are time-consuming and invasive, and are generally not practical for use by thermal comfort researchers. Instead, these researchers rely on estimates, based on tables of met rates for specific activities and occupations, developed from laboratory studies (see ASHRAE, 1992; ISO, 1990; 1994). In most studies, an average met rate is assumed for the group (usually 1.2 met for sedentary office work). More recent studies ask occupants to record their activities over the last hour, and this information is used to develop a more accurate average for the group, or individualised met estimates for each participant (Cena, 1994).

Goto, Toftum, de Dear & Fanger (2002) noted that *"activity level is probably one of the least well-described parameters of all the parameters that affect thermal sensation, comfort and temperature preferences indoors"* (p.1038). Current met tables provide information for the 'average' person, and as such do not accurately reflect differences between people or contexts. The met rate for a given activity is argued to be influenced by a person's body mass, body type, fitness, and blood flow (Goto et al, 2002; Zhang, Huizenga, Arens & Tu, 2001). The vigour with which activities are performed can also affect met values (Humphreys, 1994). Fanger (1992; 1994) noted that periods of stressful activity result in greater muscle tension, and could increase met rates for typical office tasks up to 1.5 met. Wyon (1975) also found that performing mental tasks could increase activity levels up to 1.3 met. Rowe (2001) conducted a two-year study in Sydney, during which 144 occupants completed 1,627 activity checklists. The findings showed that the average met rate for the sample was 1.2 (as is used in most office-based thermal comfort studies), but that met ranged from 1.0 to 1.9 between people and over time. A study of 24 participants, by Goto et al (2002), found that as little as five minutes of activity could affect thermal sensation levels. It also took participants around fifteen minutes to return to pre-activity levels of thermal sensation, suggesting that met estimations calculated from activity checklists be weighted for more recent activities. Overall, Havenith et al (2002) concluded that current met tables are not sufficiently accurate, and that more information is needed on metabolic rates, particularly for activities below 2.0.

Using weighted activity checklists and referring to the most recently available met tables can, therefore, improve the accuracy of met values used in thermal comfort studies (Olesen & Parsons, 2002). Brager et al (1994), for example, found that increasing met up to 1.2 (from their original estimate of 1.12) improved the fit between predicted and actual thermal sensations. However, even with such adjustments, *"it is commonly not possible in practical applications to obtain a highly accurate estimate of metabolic heat production"* (Havenith et al, 2002, p.590).

Analyses using the ASHRAE RP-844 database (Humphreys & Nicol, 2002) showed that the PMV's accuracy varied according to met rate. The PMV model best predicted actual thermal sensation for activity levels below 1.4 met. Above 1.8 met, PMV overestimated actual thermal sensation by up to one scale unit. This trend is also supported by analyses from other researchers (e.g. de Dear & Brager, 2002; Goto et al, 2002).

Overall, measurement error, particularly in relation to met and clo estimates can be considerably problematic to the accuracy of the PMV model. Using the ASHRAE RP-884 database, Humphreys and Nicol (2002) reanalysed the relationship between predicted and actual thermal sensation, after making what they considered to be reasonable adjustments for measurement error. Although these adjustments were in themselves an estimation, these researchers concluded that measurement error reduced the accuracy of the PMV model by around 20 to 25%, when the database was treated as a whole. However, although measurement error certainly contributes to the PMV's accuracy, several researchers have shown that the discrepancy between actual and predicted thermal sensation exceeds that which could reasonably be attributed to such errors (e.g. Brager et al, 1994; Oseland, 1994; Rowe, 2001; Schiller, 1990). This suggests that other factors, principally those related to context, affect the validity of the PMV model.

4.0 Contextual Assumptions

De Dear and Brager (2001) noted that *"current thermal comfort standards and the models underpinning them purport to be equally applicable across all types of building, ventilation, occupancy pattern and climate zone"* (p.100). If these assumptions are incorrect, however, they could act as sources of bias for PMV predictions (Humphreys & Nicol, 2000). In the following sections, we discuss assumptions made with respect to individual differences, building differences, climatic differences, and adaptation.

4.1 Individual Differences

Fanger's (1967; 1970) original studies were conducted using white, college-age participants. The model resulting from these studies might not, therefore, be equally valid for other occupant populations. Fanger conducted a series of experiments to investigate the effects of individual differences on PMV predictions (see Fanger, 1970). On the basis of these studies, Fanger concluded that the neutral temperature of a large group of people was not dependent on age, gender, menstrual cycle, race, obesity, time of day, or physiological acclimatisation. It is worth noting that these experiments held clothing and activity levels constant. Therefore, Fanger (1970) was not proposing that individuals do not differ, but rather than any meaningful differences could be accounted for by the clothing insulation (clo) and activity level (met) elements of the PMV model.

Since these initial experiments were conducted, there has been little additional work on the question of individual differences. Of the analyses that have been performed, most attention has been paid to gender and physiological acclimatisation.

Earlier studies in which gender was compared generally support Fanger's assumption that males and females have largely similar neutral temperatures (e.g. Fanger & Langkilde, 1975; Nevins et al, 1966; Rohles, 1974; Rohles & Nevins, 1971; Wyon et al, 1972; Yaglou & Messer, 1941). More recent studies (e.g. Cena & de Dear, 2001; de Dear et al, 1993; Grivel & Candas, 1991; Parsons & Webb, 1997 (cited in Parsons, 2002)) also reached comparable conclusions. It is interesting to note that some of these studies support a trend towards slightly higher neutral temperatures for females, typically around 0.3-0.5^{o}C. However, the majority of these findings were not statistically significant, and this trend is not consistent across studies.

A clearer finding from comparisons of gender is that females tend to be more sensitive to changes in temperature away from neutral. Fanger's (1970) original studies in this area showed that the regression equations relating temperature to thermal sensation had a steeper slope for females as compared to males. This increased sensitivity for females was shown in a recent climate chamber study on 198 participants (Zhu et al, 2002), and is also suggested by other investigations (e.g. de Dear et al, 1993; Cena & de Dear, 2001). These findings indicate that, as temperatures move away from neutral, the thermal sensation of females will change more rapidly than that of males, and females will accordingly become relatively more dissatisfied with their thermal environment.

Overall, researchers remain in disagreement as to the practical significance of gender differences. In the above studies, clothing and activity levels were controlled for. When these factors are not accounted for, the differences between male and female neutral temperatures tend to be larger (e.g. Nakano, Tanabe & Kimura, 2002), primarily because females tend to wear lighter clothing than males (ASHRAE, 2001). Therefore, when accurate clo and met values are used, it is likely that gender differences will have a minimal effect on PMV predictions. However, obtaining realistic clo and met values is challenging, and separate estimates for males and females are rarely used in practise. Therefore, practical applications of the PMV model might be compromised by the indirect effects of gender on clo estimations.

Physiological acclimatisation concerns whether an individual's physiological processes can adapt, to create a neutral temperature that is based on the climate they are exposed to. This process occurs at the physiological level, and is different from changes in behaviour or expectations that different environments might create[3].

Fanger conducted a series of climate chamber experiments to investigate the existence of physiological acclimatisation (Fanger, 1970; Fanger, Hojbjere & Thomsen, 1977; Olesen & Fanger, 1971). The study of one participant, exposed to 35°C temperatures in a climate chamber, found no significant change in his neutral temperature over a ten-day period. In further studies, native participants from Denmark and the United States were compared to native participants from the Tropics, and participants regularly exposed to cold environments (meat packing workers and cold water swimmers). Participants' physiological processes (sweat rate, heart rate, etc) were found to differ only slightly between the groups. The only significant finding from these comparisons was that the meat packers' neutral temperature was 1°C lower than that of non-cold exposed participants. Olesen and Fanger (1971) argued that this difference was *"so moderate as to be of minor importance in practise"* (p.38), and concluded that people are not able to physiologically adapt to change their neutral temperatures.

A more recent study on physiological acclimatisation supports Fanger's conclusions. In this study (Brierly, 1996 (cited in Parsons, 2002)), the physiological processes of six male college students were measured in detail during a four-day acclimatisation program, in which temperatures were increased from 23 to 45°C. Small changes in physiological processes were observed, including increased sweat rate, decreased heat rate, and changes in core temperature, but *"these changes were unlikely to be of practical significance in terms of thermal comfort"* (Parsons, 2002, p.596). Other studies (e.g. de Dear, et al, 1991; Tanabe & Kimura, 1994) found no significant difference in neutral temperatures between native participants from different parts of the world.

However, reviews of the thermal comfort literature have suggested that people from different climatic regions do differ in their neutral temperatures. Humphreys (1994) and Oseland and Humphreys(1994), both presented the results of climate chamber experiments from around the world, in which clo and met were controlled. These studies, including those by Chung and Tong (1990), Tanabe, Kimura, and Hara (1987), and Tappuni, Al-Azzan, Pack, and Al-Bazi (1989), found neutral temperatures ranging from 24.9 to 29°C. Of particular interest is the study by Abdulshukor (1993, cited in Humphreys, 1994), in which Malaysian participants living in Malaysia and England were found to prefer neutral temperatures of 28.7°C and 25.7°C

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[3] Behavioural and psychological adaptation will be discussed at a later point in this review.

respectively. These findings give some support to the notion that physiological acclimatisation might occur. However, it is unclear from these reviews whether methodological differences might account for these findings. In addition, because physiological measures were not documented in these reviews, it is not clear whether these differences reflect changes in physiology, or whether they might be caused by other contextual factors, for example cultural and social expectations.

A more established finding is that physiological acclimatisation can influence occupants' sensitivity to changes in temperature. Appropriately acclimatised occupants are better able to tolerate conditions that are warmer or cooler than neutral, in part because of changes in sweat rate, and are therefore less likely to find the thermal conditions uncomfortable (ASHRAE, 2001; Brierly, 1996 (cited in Parsons, 2002); Fanger, 1970; Tao, 1990). Within a study population, this effect is likely to be minimal, as acclimatisation to heat or cold stress typically occurs within two weeks (Fanger, 1970). However, this phenomenon could explain some of the differences in thermal sensitivity that occur between studies.

Overall, there is little evidence to suggest that neutral temperature is influenced by physiological acclimatisation, although sensitivity to temperature change is likely to be affected. As with gender, differences between physiologically acclimatised groups are likely to be larger when clothing and activity levels are not accounted for (e.g. Nakano et al, 2002). Therefore, careful clo and met estimations should be included, and should reflect the clothing and activity rates typical for the study location (ASHRAE, 2001). However, differences between groups are probably more influenced by cultural and social expectations and behaviour, than by changes in physiology.

4.2 Building Differences

The PMV model was developed from laboratory studies, and the effects of building type were not investigated during its development. Studies that have compared PMV applications in naturally ventilated and air conditioned buildings suggest that there are differences based on building type.

A number of studies have shown that the observed neutral temperature in air-conditioned buildings differs from that in naturally ventilated buildings. De Dear and Auliciems (1985), for example, found differences ranging from 1.3 to 1.7^{o}C between building types in Australia. Similarly, Busch (1992) reported that neutral temperatures in naturally ventilated buildings in Bangkok were 2.7^{o}C higher than those found in air-conditioned buildings. Oseland (1996) also found that measured neutral temperatures differed between building types, in the range of 1.4 to 2.2^{o}C.

More importantly, researchers have found that PMV predictions agree with actual thermal sensation better in air-conditioned buildings, as compared to naturally ventilated buildings. De Dear and Auliciems (1985), for example, found that PMV predictions for air-conditioned buildings were between 0.8^{o}C higher and 0.6^{o}C lower than reported neutral temperatures. Predictions in naturally ventilated buildings were, by comparison, between 0.6^{o}C lower than 2.1^{o}C higher than observed neutral temperatures. Oseland (1996) also found that the PMV was a good predictor in air-conditioned buildings, whereas the model over-predicted neutral temperatures in naturally ventilated buildings by as much as 3.6^{o}C. Busch (1990) reported a similar trend, with PMV over-predicting neutral temperatures in naturally ventilated buildings by 3.4^{o}C, but over-predicting air-conditioned buildings by only 0.8^{o}C. Finally, de Dear et al (1991) found that PMV under-predicted neutral temperatures in air-conditioned buildings by 0.2^{o}C, but over-predicted them in naturally ventilated buildings by 2.8^{o}C. Brager and de Dear (1998) reviewed these, and other studies, concluding that the predicted neutral temperature in air-conditioned buildings was generally much closer to the actual neutral temperature, as compared to the predicted and actual temperatures in naturally ventilated buildings. A number of studies have also suggested that occupants in naturally ventilated buildings are more tolerant of a wider range of temperatures, as compared to air-conditioned building occupants (e.g. Busch, 1992; Nicol & Humphreys, 1972; Oseland, 1996; Paciuk & Becker, 2002).

These trends are also supported by analyses conducted on the ASHRAE RP-884 database. De Dear and Brager (1998) analysed 99 buildings from this database, finding that there were larger differences between PMV and actual thermal sensation in naturally ventilated buildings. Air-conditioned occupants were also reported to find a narrower range of temperatures comfortable, and were more than twice as sensitive to temperature deviations away from neutral, as compared to naturally ventilated occupants. Similar findings were also reported by de Dear and Brager (2002).

Humphreys and Nicol (2002) also compared naturally ventilated and air-conditioned buildings from the ASHRAE RP-884 database. These researchers found that in 35 out of 41 naturally ventilated buildings (i.e. 85%), discrepancies between PMV and actual thermal sensations exceeded 0.25 scale units (i.e. more than could be reasonably attributed to random error). In eight of these buildings, the difference between PMV and actual thermal sensation was greater than one scale unit. By comparison, deviations of more than 0.25 scale units were found in only 49 out of 101 air-conditioned buildings analysed (i.e. 49%). Taken together, these researchers found that PMV overestimated actual thermal sensation in naturally ventilated buildings by an average of 0.26 scale units, whereas the model underestimated actual thermal sensation in air-conditioned buildings by an average of only 0.02 scale units. It is important to note that discrepancies between predicted and actual thermal sensation were found in both types of building, and *"...for the majority of buildings, whether NV* [naturally ventilated] *or AC* [air-conditioned]*, PMV gave a misleading value for the group comfort vote"* (Humphreys & Nicol, 2002, p.676). However, these analyses do support the assertion that the PMV model is a better predictor of thermal sensation in air-conditioned buildings.

Two reasons have commonly been cited to explain the differences in the PMV's accuracy between building types. These factors are the effects of outdoor climate, and the influence of behavioural and psychological adaptation, and are discussed in the following sections.

4.3 Outdoor Climate

The PMV model does not directly address the influence of outdoor climate. However, it was noted above that studies conducted in different parts of the world reported different neutral temperatures, suggesting that outdoor climate could have an influence on thermal sensation. A number of recent field studies have also suggested that neutral temperatures differ by climate or season (e.g. Cena & de Dear, 2001; de Dear et al, 1993; Oseland, 1996). In general, occupants in warmer climates or seasons tend to report warmer neutral temperatures (de Dear & Brager, 1998).

Several researchers have developed relationships between thermal sensation and outdoor temperature. Nicol & Humphreys (1972), for example, examined the results of a large number of field studies from around the world, and developed an equation that related thermal sensation to mean monthly outdoor temperature. Similar analyses have been conducted by Humphreys (1981), and more recently by de Dear & Brager (1998; 2001), using the ASHRAE RP-884 database. In all of these cases, mean monthly outdoor temperature was found to be a significant predictor of occupants' thermal sensation. Humphreys and Nicol (1990) also found that a 'running' mean, that gave greater weight to the outdoor temperature of more recent days, improved the relationship between outdoor temperature and thermal sensation.

Outdoor climate has been found to have a stronger influence on the thermal sensations of naturally ventilated occupants, as compared to those in air-conditioned buildings (de Dear & Brager, 1998; 2001; Humphreys, 1981; 1994). In naturally ventilated buildings, outdoor temperature has been shown to be linearly related to neutral temperature, to account for a large percentage of the variance in neutral temperatures, and to often be a better predictor of thermal sensation than the PMV model (e.g. Auliciems, 1981; de Dear & Auliciems, 1985; de Dear & Brager, 2001). In air-conditioned buildings, the relationship between outdoor temperature and neutral temperature is more complex, non-linear, and generally less influential (de Dear & Brager, 2001; Humphreys, 1994).

To some extent, the effects of outdoor climate are accounted for indirectly in the PMV model, through the inclusion of clothing values. Clo has been found to be related to outdoor temperature (e.g. Morgan, et al, 2002), and this relationship is reflected in the separate summer and winter thermal conditions recommended by standards agencies (ASHRAE, 1992; ISO, 1994). However, de Dear and Brager's (1998) analysis suggested that the differences in thermal sensation related to outdoor temperature were larger than could be explained merely by differences in clothing levels. Humphreys (1994) argued that outdoor temperature is a useful predictor of thermal sensation, particularly for naturally ventilated buildings, because it not only accounts for clothing values, but also acts as an indirect measure for other factors which influence thermal comfort. The most important of these factors relates to behavioural and psychological adaptation, and is discussed below.

4.4 Behavioural and Psychological Adaptation

Brager and de Dear (1998) noted that *"heat balance models view the person as a passive recipient of thermal stimuli"* (p.84). However, a growing number of researchers have acknowledged that occupants interact with their environments, and that they will adapt their behaviours and expectations with respect to thermal comfort (e.g. Baker & Standeven, 1996; Benton et al, 1990; Brager & de Dear, 1998; Cena et al, 1986; de Dear & Brager, 2001; 2002; Humphreys, 1994). Humphreys (1994) commented that *"characteristically, people seek to be comfortable, and take actions to secure thermal comfort; the motivation to do so is powerful"* (p.60).

Behavioural adaptation refers to the actions that occupants might take to achieve comfortable thermal conditions. These behaviours include opening windows, adjusting blinds or shading devices, operating fans, adjusting thermostats or blocking ventilation outlets, changing clothing, moving to a different room, modifying activity levels, and even consuming hot or cold food and drinks (Baker & Standeven, 1996; Brager & de Dear,1998; Humphreys, 1994; Oseland & Humphreys, 1994). Baker and Standeven (1996) observed office occupants in Greece, to investigate their behavioural adaptations. During 863 observed subject hours, these researchers recorded 273 adjustments to the environmental aspects of the room, and 62 clothing adjustments. Occupants also reported that the outdoor temperature had influenced their choice of clothing for the day. Morgan et al's (2002) study found that outdoor temperatures for the previous day influenced clothing choices, and termed this phenomenon 'weather memory'.

In addition to behavioural adjustments, occupants might also modify their expectations and attitudes towards the thermal environment. This psychological adaptation is argued to be influenced by culture, social norms, and previous experience, and is likely to be context dependent (Baker & Standeven, 1996; Cena, 1994, Oseland, 1995). Oseland (1995) tested this assumption, by comparing 30 occupants, who wore the same clothing and engaged in the same activities, while in home, office and climate chamber environments. Occupants' neutral temperatures were found to differ between the three contexts, suggesting that previous experience in these spaces, or the perceptions elicited by these surroundings had shaped their expectations. Other studies also support a context effect (e.g. Baille et al, 1987; Cena et al, 1990).

Humphreys (1994) argues that, if there are no constraints placed upon adaptation processes, then over time neutral temperatures will come to be similar to air temperatures. The occupant will adapt both the thermal environment and their own expectations, until a comfortable situation exists. However, if constraints, such as wealth, climate, social norms, or organisational policies, restrict occupants' opportunities to adapt, this natural process will not occur. Differences in building design (i.e. naturally ventilated vs. air-conditioned buildings) are argued to constrain opportunities for adaptation (Baker & Standeven, 1996; de Dear & Brager, 2001; Humphreys, 1994). Occupants in naturally ventilated buildings typically have more scope to modify their environments, because the building is not tightly sealed or mechanically controlled. In addition, indoor temperatures in naturally ventilated buildings tend to follow outdoor temperatures more closely, whereas air-conditioned buildings are designed to achieve a narrow, standardised range of thermal conditions. This means that air-conditioned occupants come to expect closely defined temperature conditions, and are more likely to feel dissatisfied if temperatures stray outside of this range (Baker & Standeven, 1996; de Dear & Brager, 2001; 2002). De Dear and Brager (2002) concluded that *"indoor comfort temperatures in NV* [naturally ventilated] *buildings are strongly influenced by shifting thermal expectations resulting from a combination of higher levels of perceived control, and a greater diversity of thermal experiences in such buildings"* (p.553).

Proponents of the adaptive approach argue that many of the adaptive opportunities available to naturally ventilated occupants are reflected in outdoor temperature levels. For this reason, an adaptive model of thermal comfort has been proposed, for use in naturally ventilated buildings, which links mean monthly outdoor temperature to occupants thermal sensations (Brager & de Dear, 1998; de Dear & Brager, 2001; 2002).

Taken together, evidence on the contextual assumptions discussed above suggests that the PMV model is more appropriate for predicting thermal sensation in certain contexts. Although there is little evidence for consistent differences between individuals (other than those accounted for in clo and met), the PMV model predicts thermal sensation more accurately in air-conditioned buildings, as compared to naturally ventilated buildings. These differences in predictive ability can be explained, to a large extent, by the lesser dependence of air-conditioned buildings on outdoor temperatures, and the reduced opportunities for adaptation, as compared to naturally ventilated buildings.

5.0 Conclusions – Fanger's PMV Model

Fanger's PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people in a space.

In our review of the literature, we found that the PMV model is not always a good predictor of actual thermal sensation, particularly in field study settings. Discrepancies between actual and predicted neutral temperatures reflect the difficulties inherent in obtaining accurate measures of clothing insulation and metabolic rate. In most practical settings, poor estimations of these two variables are likely to reduce the accuracy of PMV predictions. Our review also suggested that bias in PMV predictions varies by context, and is more accurate in air-conditioned buildings than in naturally ventilated ones, in part because of the influence of outdoor temperature, and opportunities for adaptation.

Humphreys and Nicol's (2002) analysis of the ASHRAE RP-884 database provides a concise summary of the biases inherent in the PMV model. As has been mentioned previously, these researchers found that the PMV predicted actual thermal sensation most accurately for clothing insulation in the range 0.3 to 1.2 clo, for activity levels below 1.4 met, and for air-conditioned buildings. In addition, Humphreys and Nicol's (2002) analyses indicated that bias in the PMV's prediction was less severe for room temperatures below 27^{o}C, for air velocities less than 0.2 m/s, and for relative humidity below 60%. Therefore, although these researchers noted that the PMV has a bias-free range of conditions that is more restricted than has previously been assumed, the conditions found in North American air-conditioned office buildings will typically fall outside those associated with serious PMV bias. Within the context of the COPE project, it is important to be aware of the limitations of Fanger's PMV model. This acknowledged, it is fair to conclude that Fanger's PMV model can be applied within the COPE project, and will produce reasonably accurate predictions of occupant thermal sensation.

6.0 Fanger's Draught Model

Draught is defined as *"an undesired cooling of the human body caused by air movement"* (ASHRAE, 2001, p.8.13), and is argued to be a common problem in office buildings (Fanger, 1992; Fanger & Christensen, 1986; Fanger et al,1988; Griefahn, Kunemund & Gehring, 2001; 2002). In addition to occupant discomfort, draughts can have implications for indoor air quality and energy use, because occupants feeling draughts sometimes react by increasing the room air temperature or covering air outlets (ASHRAE, 2001; Fanger et al, 1988).

To assess the risk of draught to occupants, the most common model used is that developed by Fanger et al (1988), on the basis of laboratory experiments. This model combines three physical parameters; air temperature, mean air velocity, and turbulence intensity, to predict the percentage of occupants dissatisfied from draught (PD).

6.1 Derivation of Fanger's Draught Model

In the 1960's and 70's, a number of researchers investigated the effects of air velocity on occupants' thermal perceptions (e.g. Ostergaard, Fanger, Olesen & Madsen, 1974; Rohles, Woods & Nevins, 1974). However, these studies focused on the effects of heat loss from the whole body, rather than local discomfort. As such, they had limited applicability to the problems encountered from draught. Other laboratory studies focused on the effects of local air movement (i.e. draught), typically directing air to the participant's head or ankles (e.g. Berglund & Foblets 1987; McIntyre, 1978; 1979). These studies determined that occupant discomfort increased with increasing air velocity, and decreasing temperature. In general, however, early studies did not ensure that occupants were thermally neutral, which made it difficult to determine the effects of draught as opposed to overall comfort.

Fanger and colleagues conducted a series of climate chamber experiments, to determine the effects of local air movement for occupants who were thermally neutral. These experiments also investigated the effects of different characteristics of the air flow.

Fanger and Pedersen (1977) investigated the effects of air temperature, air velocity, and well-defined periodically fluctuating airflows on draught perceptions, in a climate chamber. Ten participants, chosen as those most sensitive to draught from a pool of 100 people, took part in sixteen one-hour experiments. After each participant's whole body neutral temperature was determined in a pre-test, each experiment used a different combination of room temperature (4 ^{o}C above or below neutral temperature), airflow temperature (3 ^{o}C above or below chamber temperature) and frequency of airflow fluctuations (0 to1.0 Hz). During each test session, participants were exposed to five different mean air velocities (0.1 to 0.8 m/s) delivered at the back of the neck, each for a duration of eight minutes, and were asked to rate their degree of discomfort. These researchers found that draught discomfort increased with increasing air velocity and decreasing air temperature. In addition, they found that the periodically fluctuating airflows were perceived as more uncomfortable than a constant flow.

In practise, however, occupants are not usually exposed to well-defined periodically fluctuating airflows, but rather to airflows that fluctuate randomly. These airflows can be characterised by their mean air velocity and turbulence intensity (the standard deviation of the air velocity divided by the mean air velocity) (Fanger & Christensen, 1986). Several researchers have measured the characteristics of air velocities typically occurring in actual office buildings, and found that the turbulence intensity was typically in the range of 30-60%[4] (e.g. Hanzawa, Melikov & Fanger, 1987; Melikov, Hanzawa & Fanger, 1988; Thorshauge, 1982).

Fanger and Christensen (1986) conducted a climate chamber study to examine whether turbulent airflows resulted in different draught perceptions, as compared to constant airflows. 100 college age subjects, engaged in sedentary activities, took part in three, 150-minute experiments. Each experiment was conducted on a different day, and used a different air temperature (20-26^{o}C). During the first hour, the air velocity was 0.2 m/s, and subjects were encouraged to modify their clothing in order to achieve overall thermal neutrality. Following this period, clothing remained constant and the participants were exposed to six levels of mean air velocity (0.05 to 0.4 m/s), each for fifteen minutes. The turbulence intensity of all airflows was within the range typically found in office buildings (i.e. 30-60%). The airflow was directed towards the participants from behind, and participants were asked to rate whether they felt air movement, whether the air movement was uncomfortable (i.e. constituted a draught), and where on the body the draught was felt.

These researchers found that participants were most sensitive to draught at the head region. Comparing the results of their study with other, previous experiments, these researchers found that turbulent airflows increased the perception of draught, as compared to constant airflows. For example, for an air temperature of 21^{o}C, Houghten, Gutberlet and Witkowski (1938) found that 10% of participants felt draught when the air velocity was 0.3 m/s, and McIntyre (1979) found no draught discomfort at air velocities below 0.2 m/s. By comparison, in Fanger and Christensen's (1986) study, at an air temperature of 21^{o}C, air velocities of 0.2 and 0.3 m/s resulted in 30% and 50% of participants feeling uncomfortable, respectively. Overall, this study showed that when airflows were turbulent, occupants were likely to perceive draughts more often than when airflows were constant.

Based on their findings, Fanger and Christensen (1986) developed a draught chart and equation which related mean air velocity and air temperature to the percentage of people dissatisfied (i.e. voting 'uncomfortable' air movement). This draught model could be applied to situations where occupants were engaged in sedentary activities, wearing normal indoor clothing, were at, or close to, whole body thermal neutrality, and where turbulence intensity was in the range of 30 to 60%.

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[4] This range of turbulence intensity relates to office buildings with conventional mechanical ventilation. Airflows in offices with natural ventilation or displacement ventilation tend to have lower turbulence intensities.

In 1988, Fanger, Melikov, Hanzawa and Ring conducted another study, to expand Fanger and Christensen's (1986) findings. In order to be able to compare the results, this study used an identical climate chamber procedure to the previous study. However, whereas turbulence intensities in the previous study were kept within one range (i.e. 30-60%), in Fanger et al's (1988) investigation, three levels of turbulence intensity were used. In this study, 50 college age subjects took part in three, 150-minute experiments, each conducted on a different day, and each exposing participants to a different level of turbulence intensity (low: <12%; medium: 20-35%; high: >55%). The air temperature was kept constant at 23^{o}C. During each experiment, participants first achieved thermal neutrality, and were then exposed to increasing mean air velocities (0.05-0.40 m/s), at the given turbulence intensity level.

Fanger et al (1988) found that increased turbulence intensity was significantly related to increased draught perceptions. Participants were also most sensitive to draughts at the head, followed by the feet and arms. These researchers concluded that *"an air flow with high turbulence is felt as a draught by more people than a low turbulent air flow with the same mean velocity and temperature. For a given percentage of people feeling draught, a significantly higher mean velocity can be allowed when the air flow has a low turbulence intensity."* (Fanger et al, 1988, p.30).

Fanger et al (1988) used these results to extend the draught model to include turbulence intensity. This draught model has been adopted in thermal comfort standards (e.g. ASHRAE, 1992; ISO, 1994), and relates the percentage of people feeling dissatisfied from draught to the room's air temperature, mean air velocity, and turbulence intensity. The current ASHRAE thermal comfort standard states that *"the risk of draft, PD (equal to the percentage feeling draft), should be less than 15% at every point in the occupied zone."* (ASHRAE, 1992, p.16). This draught model is applicable to conditions where occupants are wearing normal indoor clothing, conducting sedentary activities, and are at, or close to, whole body thermal neutrality.

6.2 Validity of Fanger's Draught Model

As compared to Fanger's PMV model, much less work has been conducted in relation to Fanger's draught model. Very few studies have compared the predictions from Fanger's draught model with actual draught sensations. Griefahn, Kunemund and Gehring (2001; 2002) and Toftum (1994) both found that the model underestimated actual dissatisfaction from draught at low air velocities, and overestimated dissatisfaction at higher air velocities. However, these studies were both conducted in climate chambers, and the activity rates used were higher than sedentary.

In the absence of direct validation studies, an examination of the methodological and contextual limitations of Fanger's draught model can provide evidence towards its validity. Firstly, it is important to note that Fanger's draught model is based on laboratory studies, in which participants were exposed to each condition for relatively short time periods (8 to 15 minutes). It is unclear, therefore, how longer exposures to draught might affect occupants in actual office buildings. No studies on long-term draught exposure have been conducted, and so it is not known whether such exposures would aggravate draught discomfort, or whether occupants would habituate to the draught conditions.

In addition, Fanger's studies used simple two-point response scales to ask participants if they felt air movement (yes/no), and if that air movement was uncomfortable (yes/no). While it could be argued that occupants either feel a draught or not, the use of a wider scale assessing draught intensity might have been better able to capture variability between the experimental conditions.

The draught model predicts local draught discomfort when occupants are thermally neutral overall. However, there is some evidence that participants in the studies forming the model did not always have a neutral thermal sensation. In the case of Fanger and Christensen's (1986) study in particular, after the one-hour, acclimatisation period, occupants in the 20^{o}C condition and the 26^{o}C condition were slightly cool and slightly warm, respectively. In addition, as air velocity was increased during the experimental conditions, participants became progressively cooler. Despite these concerns, however, Fanger's studies did, at least, provide an acclimatisation period, to enable occupants to reach near thermal neutrality; a feature often not found in earlier studies.

In a review of air movement studies, Fountain (1991) highlighted several methodological limitations which could affect the validity of such studies in general. Of those limitations that are relevant to Fanger's work, Fountain (1991) noted that the use of multiple exposures, which followed directly after each other, might have caused participants to be influenced by the preceding conditions. This effect might also have been exacerbated because exposures were sequenced in increasing air velocity order.

In field settings, occupants might experience draughts that come from different directions, or from different distances from the body. Fountain (1991), and Oseland and Humphreys (1994), both noted that the location and direction of airflow used in studies can affect occupant responses, and some investigations on this topic have been conducted (e.g. Fanger, Ostergaard, Olesen & Lund Madsen, 1974; Ostergaard et al, 1974). However, the differential effects of airflow direction and location are not well established, and it is unclear how they might affect the accuracy of Fanger's draught model. Airflow direction and location might also affect the extent to which air movement affects overall thermal comfort, rather than draught perceptions. The ability to separate effects of overall and local discomfort is a perennial problem, which also assumes that occupants are reliably able to separate the two effects in their own perceptions (Fountain, 1991; Oseland & Humphreys, 1994; Toftum & Nielsen, 1996). As Fountain (1991) noted, *"the issue of how to interpret and compare results between local cooling and whole-body cooling experiments is probably the major cause of difference in opinion regarding the influence of air velocity"* (p.870).

Oseland (1994) noted that the majority of research on air movement has focused on the negative effects of draught. More recently, however, a number of studies have suggested that air movement can be seen as positive, when temperatures are higher. Arens, Xu, Miura, Hui, Fountain and Bauman (1998), for example, found that air velocities up to 1 m/s could be used to offset temperatures up to 29^{o}C, without air movement becoming unpleasant to occupants. Tanabe, et al (1987), and Tanabe and Kimura (1994) also found that air velocities up to 1.6 m/s were still acceptable at temperatures up to 31^{o}C. Similar studies have also supported this trend (e.g. Rohles, Konz & Jones, 1983; Xu, Kuno, Mitzutani & Saito, 1996), and turbulent airflows can increase the positive effects of air movement (e.g. Konz, Al-Wahab & Gough, 1983; Rohles et al, 1983; Wu, 1989; Xu, et al, 1996). It is important to note that these studies tended to focus on overall thermal sensations, rather than responses to local draught. However, this work does suggest that draught is perceived differently, depending on the overall thermal conditions. As Oseland and Humphreys (1994) noted, *"if the room is too warm for the occupants, the air movement is perceived as a pleasant breeze. If the room is too cold, the air movement is perceived as an unpleasant draught"* (p.9).

It has also been argued that occupants can tolerate higher air velocities, if they are given personal control over air delivery devices (e.g. Arens, et al, 1998; Fountain, Arens, de Dear, Bauman & Miura, 1994; Kubo, Isoda, Enomoto-Koshimizu, 1997). In the majority of studies on air movement in higher temperatures (see above), occupants were given control over air velocity, and allowed to select their preferred level. These studies support the greater tolerance of high air velocities in these conditions, but also pose a methodological problem. More specifically, because the studies where personal control was used also tended to be studies at higher air temperatures, it is not clear which of these factors affects occupants' responses to air movement. To date, no studies have investigated occupant responses to the same air velocity-temperature combinations, with and without personal control.

Despite this confounding problem, it does appear that, when room temperatures are higher, relatively high air velocities, controlled by occupants, can still be perceived as pleasant. Opportunities to provide these conditions has been integrated into ASHRAE *Standard 55* (ASHRAE 1992), where air velocities greater than 0.2 m/s can be used to offset higher temperatures, providing that air velocity is within the occupants' control.

6.3 Conclusions - Fanger's Draught Model

Fanger's draught model combines three physical variables (air temperature, mean air velocity, and turbulence intensity) into an index that predicts the percentage of occupants dissatisfied from draught. In comparison to Fanger's PMV model, much less work has focused on the validity of this model. Our review highlighted a number of methodological and contextual limitations that could potentially undermine the accuracy of the model's predictions. Among the most interesting, recent studies suggested that, at higher air temperatures, draughts might be perceived as pleasant air movement, rather than unwanted discomfort. There was also evidence to suggest that occupants were more tolerant of draughts if they had personal control over air delivery devices.

Based on the available evidence, we found no reason to suggest that predictions based on Fanger's draught model would be seriously biased. This is particularly the case if the model is used within the assumptions that it was originally developed for. More specifically, for occupants wearing normal indoor clothing, performing sedentary activities, at or near thermal neutrality, and without personal control over air velocity, Fanger's draught model can reasonably be applied without concern for serious bias.

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