Environmental Conditions and Occupant Perceptions in European Office Buildings

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ABSTRACT

This is a preliminary report regarding a portion of the environmental conditions and occupant comfort perceptions from a five nation, 26 building European field data collection effort. Approximately 1,000 participants were involved in this project which included twelve monthly visits to each building. Climate, building and cultural variation will be illustrated for the five countries involved - France, Greece, Portugal, Sweden and the United Kingdom (UK). Each country used identical instrumentation; questionnaires and experimental protocols imbedded in a custom hardware/software system.

The comfort survey was based on the ASHRAE model. The physical measurements included air temperature, globe temperature, relative humidity, air movement, CO_2, light, and sound levels. Where possible, connections and explanations between variables are made. Potential energy and policy ramifications are illustrated.

Introduction

Indoor environmental standards at national and international levels are largely based on laboratory studies, specifically the work of Professor Fanger of the University of Denmark (Fanger, 1970). This is reasonable since empirical studies using real occupied buildings are not only difficult and expensive to conduct but the results are very difficult to interpret. It is hard to imagine a standard based on field studies. On the other hand, standards based solely on laboratory work may be insufficient or even incorrect because the conditions in real buildings are so much more complex than laboratory experiments conducted under controlled conditions. Recent and ongoing work by de Dear and Brager (de Dear and Brager 1998) is helping to clarify and resolve the issue of the relative importance of adaptation and physics (and hence the laboratory versus empirical approaches) in determining thermal comfort.

This is a preliminary report about a project designed to help resolve or at least illuminate this problem for indoor environments in European office buildings. The results reported mostly focus on examinations of variables independently while it is well know that thermal comfort is simultaneously dependent on several variables. Much work remains to be accomplished to gain a complete and full understanding of what this data set may tell us about thermal comfort in European office buildings, but hopefully a preliminary reporting and examination of some of the data collected in this large European project will be of interest to the ACEEE audience.

The Smart Controls and Thermal Comfort (SCATS) Project will ultimately develop and test advanced HVAC controls. Early phases of the project collected environmental conditions and occupant comfort perceptions in 26 European office buildings located in France, Greece, Portugal, Sweden and the UK. Field data collection ran from June 1998 until October of 1999. Most buildings have twelve sets of measurements covering all seasons of the year. Since it is a field study subject to the impacts of unexpected events, some building specific data sets do not encompass twelve sequential monthly visits. In addition, over the course of the study there was a general drop in the number of participants in each building and in the percentage of successful surveys among the recruited participants. However, the team was able to complete 4,655 sets of physical measurements with concurrent occupant perceptions. Naturally, not all of these data are completely usable, as there were occasional hardware failures and errors of transcription.

This is a large data set with a large number of variables. The physical measurements included air temperature, globe temperature, relative humidity, air movement, CO_2 level, light level, and sound level. In addition a complete comfort survey, an estimation of clothing, activity levels and identification of control settings are included with each set of physical measurements. John Solomon of the University of North London developed the instrumentation suite and operational software. There is simply too much information to be completely summarised in this twelve-page paper. This report is therefore a summary of a few items of interest. The oral presentation at the Summer Study will include graphical representations of additional findings.

The Sample

The project team wanted a set of office buildings that was representative of national building stocks. Viable statistics and conclusions, especially for the relatively small sample size of the buildings, demand a minimisation of bias. However, for all the countries, recruiting the buildings was difficult and the sample is probably biased toward buildings that the occupants find thermally unacceptable. "For the good of science and mankind", was not a sufficient recruitment incentive for most buildings, they wanted something in return such as a better understanding of the dissatisfaction of the occupants with the environment. Still, the buildings that were recruited seem to the researchers to be quite typical of the current office building stock in these five countries.

Occupant density was reasonably consistent within each country, but there were differences between countries - Sweden having the lowest density, Greece and Portugal had the highest with France and the UK being in between. All of the buildings had operable windows and almost all occupants had potential visual contact with the outside. Essentially all the occupants had a dedicated computer with all of the subjects spending at least part of their workday using the VDU and keyboard.

The building shells and HVAC systems were quite different between countries yet reasonably similar within each country. The buildings in Sweden had shells with very high thermal integrity - high levels of insulation, triple glazing and minimisation of thermal bridging. At the other extreme were Portugal and Greece with minimal or no insulation, mostly single glazing, air leaks and thermal bridges. The thermal shell of the buildings in France and the UK were more similar to the buildings in Portugal and Greece than to the buildings in Sweden while the climate they face is closer to the climate of southern Sweden than to southern Europe.

The southern European countries had significant variation of HVAC systems installed, with those in Portugal being minimal. In Greece the buildings had a mixture of modern central systems, minimal packaged units or just simple heaters and operable windows. These two countries had exhaust only ventilation in many of the buildings. The buildings in France all had modern central heating systems and central exhaust ventilation with the air supply coming from slots around the windows. Some buildings had mechanical cooling. The United Kingdom had a wide variation. All buildings had central heating systems, but only about half had mechanical ventilation or cooling. Once again, Sweden is the extreme with fan-powered ventilation - both exhaust and supply for all the buildings. The supply air was heated or cooled as conditions demanded and all buildings had exhaust air heat recovery. In addition, all the Swedish buildings had perimeter radiators and areas of high heat gain had ceiling mounted radiant cooling panels (chilled beams as they are called locally).

The human participants in the study appeared to be representative of the building occupants. Both sexes, all ages, and most working levels were represented. It was more difficult to succeed in completing surveys with individuals occupying management positions, as they seemed to be away from their offices a higher percentage of the time than are normal professionals. Again, because the participants volunteered, there may be a bias based on dissatisfaction with the indoor environment.

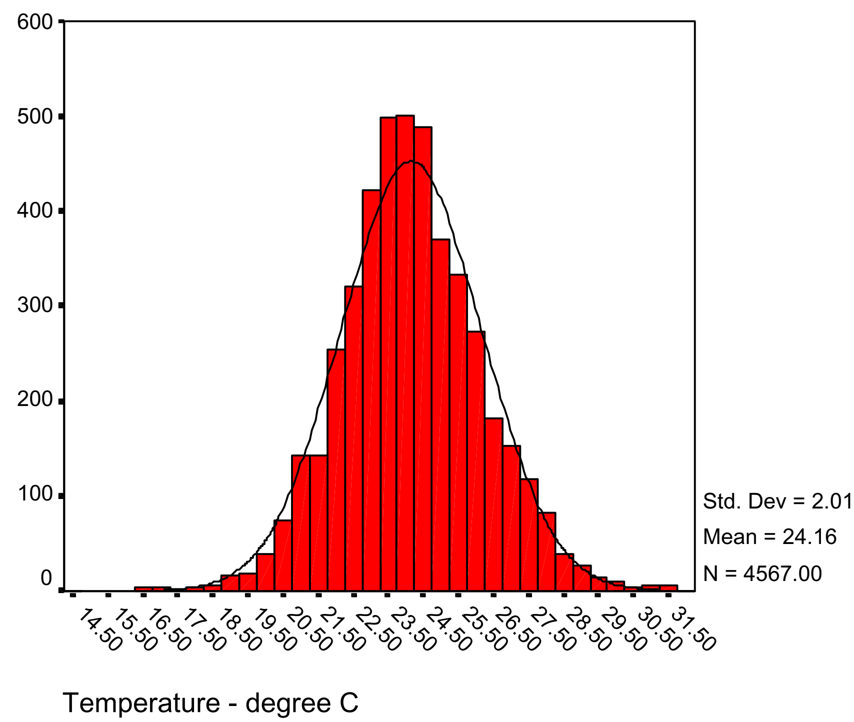

Figure 1 Indoor Temperatures (°C) all Countries

Indoor Temperature

Taken together, Figure 1 and Table 1 provide a good perspective on the temperature variation in European office buildings. Figure 1 illustrates the total range of temperatures over a year in the sample buildings. Perfect temperature control could not be expected especially when some of the buildings had minimal HVAC systems. The whole sample mean temperature of 24.2°C appears to be reasonable yet above the European guidelines of maintaining interior temperatures between 22 and 24°C. Figure 1 also illustrates the distribution of temperatures, ranging from 14.5 to 31.5°C similar to a normal distribution. The temperature distributions among the buildings within each country were quite similar while distributions between countries had some variation as shown in Table 1.

	France		Greece		Portugal		Sweden		UK	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Annual	24.7	2.4	26.3	2.2	23.7	2.3	23.3	1.0	24.5	1.4
Summer	27.2	2.1	28.0	1.3	26.3	1.3	24.0	1.0	24.9	1.6
Winter	23.3	1.6	25.6	1.3	21.7	1.7	22.8	0.9	24.3	1.0
Autumn	23.9	2.0	26.0	2.3	23.9	1.9	23.1	0.8	24.0	1.3
Spring	25.5	1.1	25.5	2.0	23.9	1.6	23.2	0.8	24.8	1.4

Table 1 Country Specific Indoor Temperatures (°C), Mean and Standard Deviation (SD) by Season

Table 1 is an illustration of the two dominant kinds of variation evident in the indoor temperature data. Individual countries have different temperature distributions across the seasons. It is easiest to start with Sweden where indoor temperatures are very well controlled. Indoor temperatures are 1.2°C colder in winter than in summer and there is little variation between buildings and location within the buildings or month. The indoor temperatures of buildings in the UK were almost as well controlled as those of Sweden and in fact have an even smaller winter/summer difference of 0.6°C. In the UK, summer variations especially were higher and in all months the indoor temperatures were almost 1°C warmer than in Sweden. The indoor temperatures in Sweden in all months appeared to be lower and more closely controlled than in all the other countries. The one exception was winter in Portugal, which on average was almost 1°C colder than in Sweden. France, Greece, and Portugal all had warmer summer indoor conditions than in Sweden and the UK. Greece had the warmest indoor temperature; 3°C warmer on average than Sweden and also with significant variation, especially in autumn and spring. The largest seasonal variation was in Portugal with an average difference between winter and summer of 4.6°C. For the same statistics France had a 3.9°C difference, and Greece had a 2.4°C difference.

Temperature Perceptions

Most current literature on thermal comfort uses the phrase "thermal sensation" to describe an individual's perception of their immediate environment. In this report, the phrase "temperature perception" in used as it communicates more directly the fact that we are trying to understand occupants' perceptions of the temperature of their surroundings. As used in this report, the two different terms should be considered equivalent in meaning. Temperature perceptions (thermal sensations), using the ASHRAE 7-point scale were collected concurrent with the indoor temperature measurements (ASHRAE). The ASHRAE 7-point thermal comfort scale is:

1	2	3	4	5	6	7
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

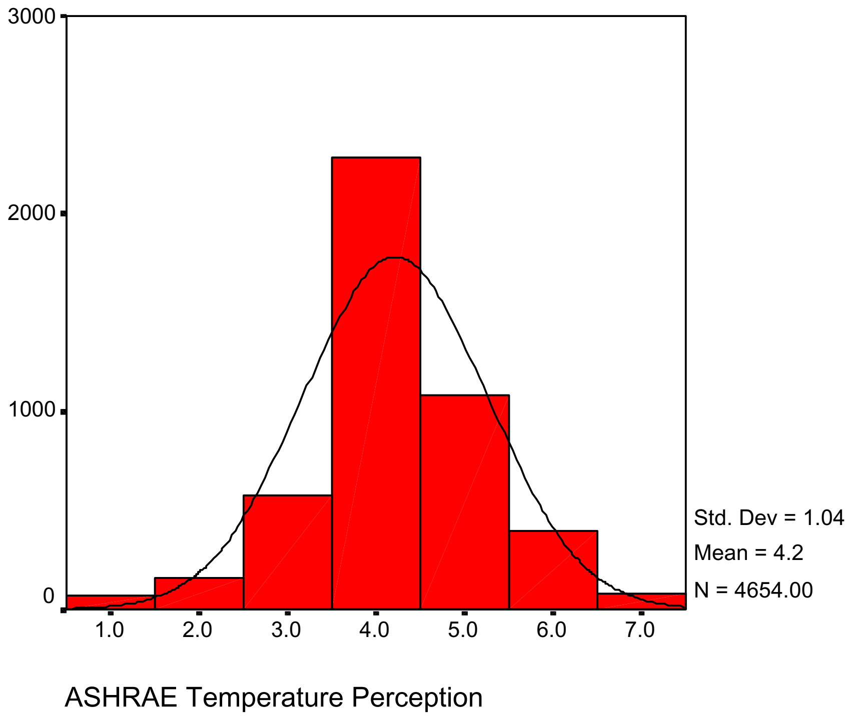

Figure 2 Indoor Temperature Perception, ASHRAE 7 Point Scale

Table 2 illustrates the country and seasonal variation of the measured thermal comfort perceptions while Figure 2 provides a graphical illustration of the data for all countries and seasons. Generally the thermal perceptions of the occupants are close to neutrality. Of the 4,654 total valid responses 2,284 were a thermal neutral response of 4. In addition, 1085 responses were slightly warm and 573 were slightly cool. Another way to interpret the data is to say that 712 responses or 15.3% were dissatisfied with the temperature at the time of the surveys (responses of 1,2, 6 or 7).

	France		Greece		Portugal		Sweden		UK	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Annual	4.4	1.1	4.1	1.1	4.2	0.9	4.0	0.7	4.4	1.3
Summer	4.8	1.1	4.1	1.2	4.4	0.9	4.2	0.8	4.3	1.4
Winter	4.1	1.1	4.1	1.0	4.0	0.9	4.0	0.8	4.5	1.2
Autumn	4.3	1.0	4.2	1.0	4.1	0.9	3.9	0.7	4.4	1.3
Spring	4.4	1.0	3.9	1.0	4.1	0.8	4.0	0.6	4.4	1.3

Table 2 Country Specific Indoor Temperature Perception (ASHRAE 7 Point Scale), Mean and Standard Deviation by Season

In Table 2 we see that there is a country specific seasonal variation in temperature perceptions just, as there is a country specific seasonal variation of temperature. The standard deviations of the temperature perceptions in Table 2 provide additional insight into how the perceptions of conditions in different countries vary. The temperatures in Swedish buildings are tightly grouped as well as the temperature perceptions. This reflects the fact that Swedish buildings deliver a high level of thermal conditioning to the occupants meeting their expectations. Except for the warm summer perceptions, the occupants in Portuguese buildings are almost as satisfied as their counterparts in Sweden. The Portuguese are thermally neutral to the coldest country specific season in the sample - their winter with and average indoor temperature of 21.7°C. On a scale of overall thermal satisfaction, the occupants of the buildings in Greece are between Portugal and Sweden. They are really very content with their indoor environment, even though the actual temperatures are significantly warmer than in most of the other countries. France and the UK appear generally to be too warm, but there is significant variation in responses indicating potential inconsistency in supplying the buildings with thermal comfort, especially in the UK.

	France		Greece		Portugal		Sweden		UK	
	°C	TP	°C	TP	°C	TP	°C	TP	°C	TP
Annual	24.7	4.4	26.3	4.1	23.7	4.3	23.3	4.0	24.5	4.4
Summer	27.2	4.8	28.0	4.1	26.3	4.4	24.0	4.2	24.9	4.3
Winter	23.3	4.1	25.6	4.1	21.7	4.0	22.8	4.0	24.3	4.5
Autumn	23.9	4.3	26.0	4.2	23.9	4.1	23.1	3.9	24.0	4.4
Spring	25.5	4.4	25.5	3.9	23.9	4.1	23.2	4.0	24.8	4.4

Table 3 Country Specific Mean Indoor Temperatures (°C) and Mean Temperature Perceptions (ASHRAE 7 Point Scale), by Season

Table 3 brings together the seasonal country specific variations in temperature and temperature feeling into a single table making comparisons easier. Without considering any of the other thermal comfort variables, it appears that there are indeed country specific and seasonal variations. Much of the table needs little further explanation. For example, a summer temperature of 24°C is a bit warm for Sweden, which feels neutral with a spring time indoor temperature of 23.2°C and a winter indoor temperature of 22.8°C. Occupants of buildings in the UK feel too warm year round on average, as are occupants in France although winter temperatures of 23.3°C are close to being neutral. In Portugal, average summer temperatures of 26.3°C are too warm but otherwise they are satisfied and, on average, absolutely neutral with a winter temperature of 21.7°C. The exception is Greece, where the occupants appear to feel almost neutral with seasonal temperatures that would be found too warm in all the other countries.

Neutral Temperature

It would be easier to compare neutral temperatures with neutral temperatures; the average temperature that would result in an average perception vote of 4 on the ASHRAE scale in each season in each country. We have a large number of seasonal measurements in all of the five countries with concurrent temperature and temperature perceptions. When graphed against each other, as in Figure 3 the temperature versus temperature perception plot looks a little odd as a continuous variable is being plotted against a whole number variable. However the technique is valid and the temperature associated with the intercept of the fitted line with temperature perceptions of 4 should represent the average neutral temperature. Figure 3 is an illustration of the technique, using data from the UK. Similar plots were used to generate the numbers in Table 4.

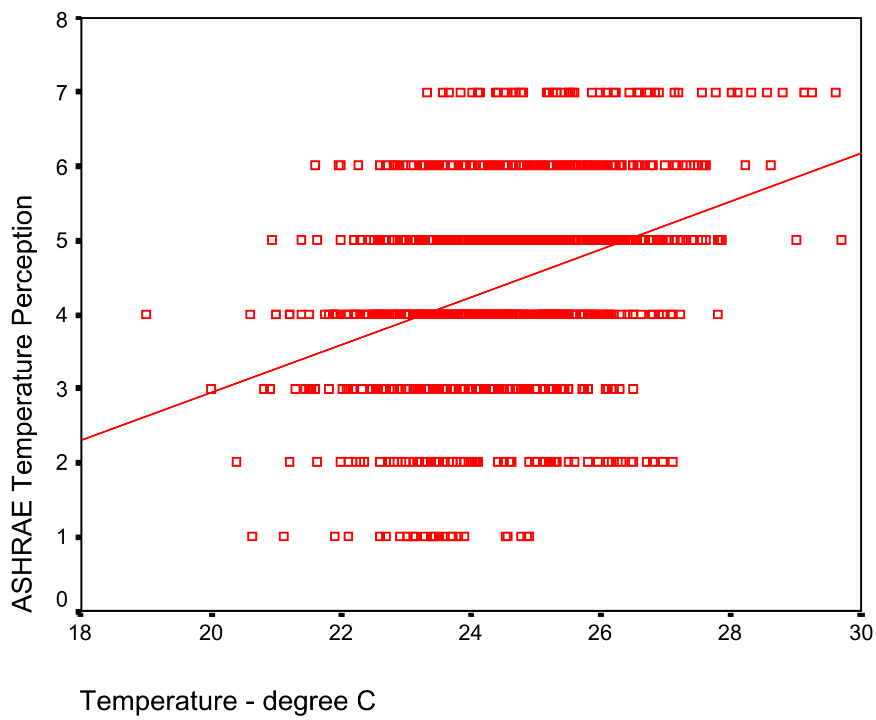

Figure 3 Annual Indoor Temperature (°C) UK vs. ASHRAE Temperature Perception

	France		Greece		Portugal		Sweden		UK	
	°C	delta	°C	delta	°C	delta	°C	delta	°C	delta
Annual	22.7	+2.0	25.7	+0.6	22.9	+0.8	23.2	+0.1	23.3	+1.2
Summer	24.7	+2.5	27.5	+0.5	25.4	+0.9	23.5	+0.5	24.2	+0.7
Winter	21.5	+1.8	25.6	0.0	21.5	+0.2	23.0	-0.2	22.9	+1.4
Autumn	22.4	+1.5	24.7	+1.3	23.9	+0.8	23.5	-0.4	22.6	+1.4
Spring	24.7	+0.8	26.3	-0.8	21.9	+2.0	23.3	-0.1	23.5	+1.3

Table 4 Estimated Country Specific Neutral Indoor Temperatures (°C), and Difference from Mean Indoor Temperature (°C) by Season

Table 4 presents the estimated neutral temperatures in each country and season along with the difference between that temperature and the average temperatures measured in the surveys. The first thing one notices is the relative paucity of negative numbers. Except for winter, autumn and spring Sweden and spring in Greece all the average measured temperatures were equal to or above the estimated neutral temperatures. In France, the annual average difference was 2.0°C while in Sweden the annual average was slightly above neutral temperature. The relatively high temperatures maintained in Greek buildings were only on average, 0.6°C higher than the average occupant's neutral temperature. There are clear seasonal variations across Europe, but there does not seem to be a common pattern. Both summer and winter conditions in France are significantly too warm while in Portugal winter is slightly above neutral and summer 0.9°C too warm. Sweden continues to demonstrate that buildings in this country are maintained year round at conditions very close to the average neutral temperature although summer conditions were maintained on average 0.5 °C too high.

Clothing

Over the course of the year, all of us adjust our clothing levels to accommodate the changing outside temperatures. Heavy sweaters are worn in the winter and lighter clothing is worn in the summer. Figure 4 shows the clothing variation by season across Europe. The mean summer Clo value is about 0.6 while the winter Clo value is about 0.9 with significant variation in all seasons. The project software calculated Clo value from a lookup table of clothing and fabric weights including a correction factor for insulation provided by the chair. The individual researchers in each country followed the same protocol in identifying clothing weights to help assure consistency in the data across countries.

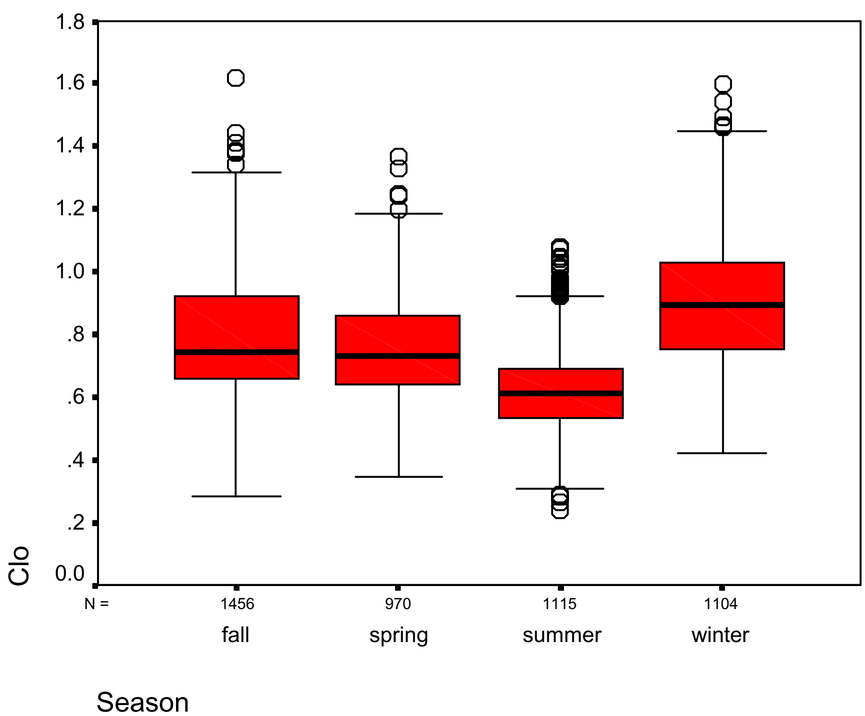

Figure 4 Clothing (Clo) by Season, All Countries

Table 5 presents the mean Clo values by country and season along with the estimated neutral temperatures. Prior work by (Humphreys and Nicol, 1995) has demonstrated that some humans adapt to temperature variation and especially will modify their clothing ensemble to fit weather conditions. This table is an illustration of that adaptation. Assuming a simplified environment where mean radiant temperature equals air temperature, light activity levels and no air movement we can estimate that every 0.1 increase in Clo values will result in a decrease in the neutral temperature of about 0.6°C (for Clo values between 0.5 and 1.0) (Fanger, 1970). This relationship was used to build Table 6. The goal is to illustrate the seasonal temperature adaptation explained solely by changes in clothing levels. The rows are the seasonal differences for each country column. The pairs of numbers are the temperature differences, with the first number being the seasonal neutral temperature difference from the annual neutral temperature for each country. For example, in France the average summer neutral temperature is 2.0°C higher than the annual average neutral temperature. The second number is the calculated difference from the annual neutral temperature that the seasonal change in Clo should produce. Again, using the summer in France as the example. Summer Clo is 0.22 lower than the annual average. This 0.22 Clo reduction should explain by itself an increase in estimated neutral temperature of 1.3°C. Similar calculations were used to complete Table 6. It is clear that individuals can and do make other temperature related adaptations besides clothing but it is interesting to note how much temperature adaptation in an average sample can be explained solely by changes in clothing levels.

	France		Greece		Portugal		Sweden		UK	
	°C	Clo	°C	Clo	°C	Clo	°C	Clo	°C	Clo
Annual	22.7	0.76	25.7	0.72	22.9	0.81	23.2	0.78	23.3	0.72
Summer	24.7	0.54	27.5	0.61	25.4	0.57	23.5	0.67	24.2	0.65
Winter	21.5	0.91	25.6	0.81	21.5	0.99	23.0	0.91	22.9	0.77
Autumn	22.4	0.81	24.7	0.71	23.9	0.79	23.5	0.82	22.6	0.77
Spring	24.7	0.72	26.3	0.79	21.9	0.80	23.3	0.77	23.5	0.69

Table 5 Estimated Country Specific Neutral Indoor Temperatures (°C), Level 4 on ASHRAE Thermal Comfort Scale and Measured Clothing Level (Clo) by Season

	France		Greece		Portugal		Sweden		UK	
Delta from annual mean	Temp	Clo	Temp	Clo	Temp	Clo	Temp	Clo	Temp	Clo
	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Summer	+2.0	+1.3	+1.8	+0.7	+2.5	+1.4	+0.3	+0.7	+0.9	+0.4
Winter	-1.2	-0.9	-0.1	-0.5	-1.4	-1.1	-0.2	-0.8	-0.4	-0.3
Autumn	+0.3	-0.3	-1.0	+0.1	+1.0	+0.1	+0.3	-0.2	-0.7	-0.3
Spring	+2.0	+0.2	+0.6	-0.4	-1.0	+0.1	+0.1	+0.1	+0.2	+0.2

Table 6 Country Specific Seasonal Neutral Temperatures Differences (°C) from Annual Average Neutral Temperatures and Estimated Temperature Difference (°C) Explained by Differences in Clo

There are clear country differences. Most of the temperature differences caused by changes in clothing do at least go in the right direction (have the same sign) as the seasonal changes from annual neutral temperature. That is always true for winter and summer, but spring and autumn don't always agree. For most seasons in most countries, the clothing change only explains part of the seasonal change in neutral temperature. Except in Sweden where in the summer and winter it appears that individuals may overcompensate their clothing ensemble to better reflect the changing outdoor conditions while the seasonal indoor temperatures have little variation. For all of the other countries, the change in Clo level can only explain part of the summer change in neutral temperature. Yet the Swedish overcompensation pattern is repeated in Greece for winter neutral conditions. The change in Clo values account for more potential change in neutral temperature than is actually seen. Conversely, in Greece and Portugal summer seasons, the change in neutral temperature is 0.9°C and 1.1°C respectively more than the change explained by changes in Clo. A very significant unexplained adaptation with a very strong winter/summer change in these two southern European countries. In France and the UK the pattern is more consistent with the Fanger model. However, the overall conclusion that one can draw from this data is that the change in clothing alone does not by itself adequately explain the seasonal changes in neutral temperatures in this sample. Additional analysis will be performed on this data in upcoming months to more fully illustrate the potential and real impacts of other comfort variables.

Carbon Dioxide

In Figure 5 we see the significant differences in CO_2 level in the sample office buildings in the five countries. In Sweden the mean level was 507ppm with very little variation. At the other extreme was Portugal where the mean value was 1099ppm with several measurements above 3015ppm, which was the maximum value that the instrument could record. France, Greece and UK were all similar, with very few readings above 1000ppm - the accepted maximum value in most standards. Stated simply, it appears that Sweden may be ventilating more aggressively than the actual conditions in the buildings require. Portugal is ventilating less than the conditions in the buildings require while the other three countries seem to have it close to standard. But, the occupant perceptions of the air quality do not relate well to the CO_2 data. On a 7 point scale where 4 is neutral and 5 is slightly good the mean air quality perceptions in the five countries were:

France	Greece	Portugal	Sweden	UK
5.2	4.8	4.3	4.2	4.9

Sweden and Portugal, the two countries with the respective best and worst quality indoor air (as indicated by CO_2 levels) record essentially identical values of occupant perceptions of indoor air quality. The other three countries have similar perceptions, which relate to similar CO_2 measurements. If CO_2 levels and air quality are correlated then Portugal should have a low value (like 2 or 3) for indoor air quality and Sweden should have a high value (like 6 or 7). From this data it does not appear that qualitative perceptions of air quality relate to measurements of CO_2. There are

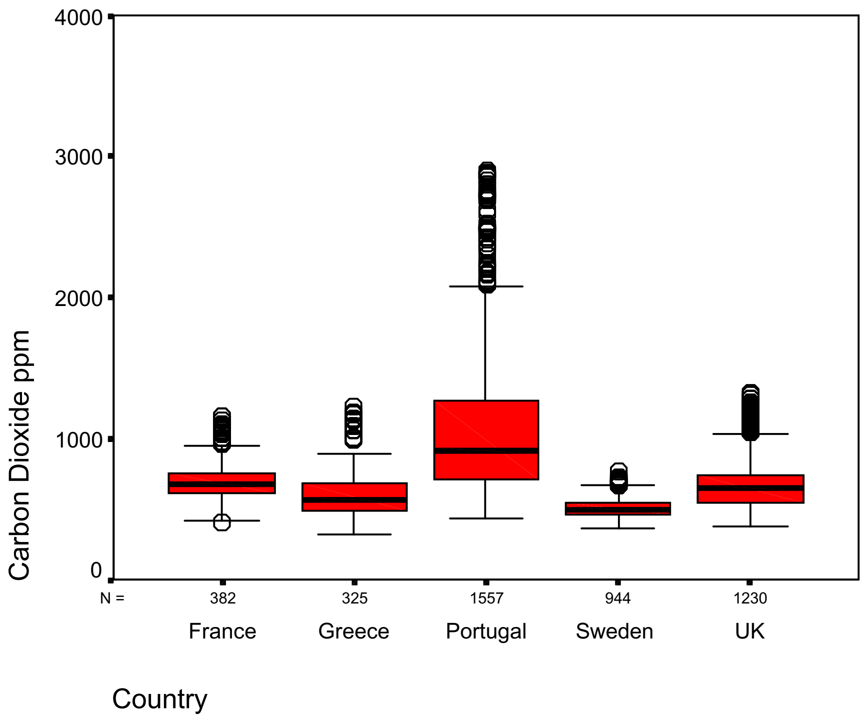

Figure 5 Carbon Dioxide by Country

clear differences in levels of CO_2 across European countries but those differences do not relate to occupants' perceptions of air quality. There may be very different air quality expectations in specific countries. For this data, building occupants in Sweden may have very high expectations and occupants in Portugal may have low expectations.

Conclusions

The conclusions (at this stage of analysis perhaps they could be more accurately called speculations) of this report are preliminary based on the partial analysis documented here. For each of the two indoor environmental variables examined, temperature and CO_2 it appears that perceptions of desirable environmental conditions do not necessarily relate well with the standards for those same variables. Generally, most individuals in these five countries feel close to neutral in all seasons despite significant variations from the standard expressed conditions. For some of these variables Portugal and Sweden represent the extremes of measured conditions while the occupants in these two countries express very similar levels of satisfaction. A possible explanation for this that office building occupants in these two countries have very different levels of environmental expectations. As the European Union grows ever closer together with employment policies allowing full mobility of workers between countries these kinds of different expectations may present significant challenges to workers and employers. A typical office worker moved from Sweden to Portugal would find many aspects of the indoor environment that would not meet Swedish expectations. Nothing in the data behind this report provides any illumination regarding the ability of a Swedish worker to adopt to the conditions in Portugal. Clearly there are numerous country to country variations. Standards developed specifically for one country may not be suitable for other countries. The EU faces a significant challenge in developing standards for all countries as the existing conditions and expectations are so different across Europe.

Delivering high levels of indoor environmental control like in Sweden does not appear to result in significant improvements in occupant satisfaction. In fact, based on seasonal clothing changes it appears that Sweden could allow indoor temperature to more closely track outdoor temperatures. The physics of clothing insulation should allow this change with little decrease in actual comfort. Naturally any such change would likely require some change in occupant expectations. In all these countries, indoor temperatures in all seasons except summer are somewhat too warm. Reducing indoor temperatures to something closer to neutral temperatures would result in energy consumption reductions for heating and energy consumption increases for cooling.

As the analysis continues, including additional variables and the interactions of multiple variables acting simultaneously it is expected that understanding of the variations seen will improve. Relative humidity, air movement, exterior conditions and building variations are all expected to have an impact on the thermal sensations of occupants. It is expected that some of the unexplained variations will be explained.

Acknowledgements

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References

The literature regarding thermal comfort is rich; listing it all would take several pages. The references noted below will provide the interested reader a starting place for further exploration of this challenging subject.

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