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Are heavyweight buildings more comfortable? The potential of thermal mass in increasing thermal comfort

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Abstract: In temperate climates, one passive design solution is to increase the heat capacity of building fabric. This design principle aims to reduce heating demand in winter and over-heating in summer; it is also coupled with more stable indoor air and radiant temperature. This may suggest that by exposing thermal mass, occupants may feel more comfortable. Although previous research based on simulations have studied this relationship, there is a lack of empirical evidence. This paper reviews the results an EU-funded research project, smart controls and thermal comfort (SCATs) to ascertain the impact of building fabric on occupants' perceived comfort. Between 1997 and 2000, twenty-six office buildings from five different countries (France, Greece, Portugal, Sweden and UK) were surveyed using a transverse questionnaire, a longitudinal questionnaire and environmental monitoring. This paper analyses the transverse questionnaires responses (N=451), in particular answers to questions on thermal perception, thermal preference and overall comfort. Results show a statistically significant relationship between building fabric heat capacity and subjective comfort (thermal perception $\chi^2(1)=3.78$, $p=0.05$ and overall comfort $\chi^2(1)=4.37$, $p<0.05$). Heavyweight buildings are reported to be more comfortable than lightweight buildings. Providing careful integration with building management, this insight may have implications on the adoption of thermal mass in new and retrofit buildings.

Keywords: Passive design, Thermal mass, Thermal comfort, Adaptive comfort

Introduction

Besides global mean surface temperature rising by at least 1.5°C by the end of the 21st century (IPCC, section 2.2.1, 2014), Europe is set to be faced with an increase in extremes climate events, in particular heat waves. Buildings will have to adapt to these new thermal conditions by applying mitigation strategies such as thermal mass, ventilation and solar shading (Hacker et al, 2005). Studies based on dynamic building simulations have shown that thermal mass has the potential to dampen indoor air temperature and therefore to reduce peaks in internal operative temperature leading to more comfortable indoor conditions (Aste et al, 2009; Tuohy, 2009; Arcuri et al, 2016). The aim of this paper is to investigate the potential of thermal mass in increasing thermal comfort using empirical evidence from an EU-funded research project, smart controls and thermal comfort (SCATs) (Nicol, 2001; Wilson et al, 2001; McCartney and Nicol, 2002).

The thermal mass effect is associated with the building's thermal capacity defined as the ability of a building to store and to release heat. In this paper, thermal capacity is used to compare heavyweight against lightweight constructions in non-steady state conditions, as temperature inside buildings vary in time and direction (indoor to outdoor and outdoor to indoor). In a temperate climate, the heat flows through the building fabric are not constant and unidirectional throughout the year or throughout the day. In summer, external temperatures may be higher than internal temperature during the day but lower during the night. These changes in heat flow result in a time shift between external and internal temperature, although both follow similar sinusoidal patterns. In summer, this delayed periodic transmittance in heat flow may alleviate the risk of overheating by absorbing solar and internal gains during the day and releasing heat at night. In this instance, the internal thermal mass should be ventilated at night, enabling it to precool before the next heating phase (Roucoult et al. 1999). As internal temperatures are dampened during occupied hours, the first hypothesis is that heavyweight buildings are more comfortable than lightweight buildings in summer. However, this elemental approach does not take into consideration other building characteristics, such as air infiltration and ventilation strategies. Occupants may only perceive this dampening effect in buildings without mechanical ventilation and cooling (Holmes and Hacker, 2007). Therefore the second hypothesis is that heavyweight naturally ventilated buildings should be more confortable that lightweight naturally ventilated buildings. Whilst the likelihood for more stable internal temperatures may lead to the assumption that heavyweight buildings are more thermally comfortable, this will certainly not always be the case and is dependent upon the interactions between the thermal mass and heating/ventilation systems, controls, scheduling and the external environment. As an example, without sufficient scheduling or set-back a heavyweight building will take longer to initially heat to comfort temperatures and may therefore be less comfortable than its lightweight equivalent over this period. Alternatively, within warm sunny periods any exposed thermal mass will help to absorb excess heat and reduce peaks in temperature. However, if this stored heat cannot be sufficiently discharged then the building is likely to experience significant and long term overheating (Roucoult et al. 1999). The predicted level of comfort therefore cannot be simply related to the thermal mass of a building but to the relationship of this mass to other aspects of the building fabric, systems and environment. Nevertheless, using statistical analysis across a wide enough dataset, overall trends are hoped to be established in this paper.

The first section will introduce the dataset and the data analysis methods applied. To follow, the second section will report on the results of the analysis. Finally the last section will discuss the findings and highlight implications to future building design.

Study design

This paper aims to review the relationship between building thermal capacity and occupants reported thermal sensation, preference and comfort.

This paper analyses a dataset collected for an EU-funded research project on smart controls and thermal comfort (SCATs) (Nicol et al, 2002). Thermal comfort surveys were conducted in 26 non-domestic buildings across five countries and eight cities in Europe (France, Greece, Portugal, Sweden and the UK). The climate classifications of the eight cities are summarised in Table 1. The sample of buildings had five different ventilation types, including (NV) naturally ventilated (heating in winter, free-running, no cooling or mechanical ventilation in summer), (AC) centrally air conditioned (heating and cooling), (MV) mechanically ventilated (no cooling in summer), (MM) mixed mode (heating in winter, cooling when needed in summer) and (PP) a mixture of AC and NV in the same building. Furthermore the sample of buildings had three different thermal capacity types, including lightweight (LW), medium- or mixed-weight (MW) and heavyweight (HW). For the purposes of this paper only LW and HW buildings were considered.

Table 1. Characteristics of the sample including building's thermal capacity (LW: lightweight, MW: medium- or mixed-weight, HW: heavyweight) and Köppen climate classification

Country	**City**	**Thermal capacity**	**Köppen Climate Classification**		
France	Lyon	2 HW, 2 MW, 1 LW	Group C - Temperate	(Cfa)	Humid subtropical
Greece	Athens	2 HW, 3 MW	Group C - Temperate	(Csa)	Hot-summer Mediterranean
Portugal	Porto	1 HW, 2 MW, 1 LW	Group C - Temperate	(Csb)	Warm-summer Mediterranean
	Afragida	1 HW	Group C - Temperate	(Csa)	Hot-summer Mediterranean
Sweden	Goteborg	1 HW, 2MW	Group C - Temperate	(Cfb)	Oceanic
	Malmo	1 MW	Group D - Continental	(Dfb)	Humid continental
	Halmstad	1 LW	Group C - Temperate	(Cfb)	Oceanic
UK	London	1 HW, 5 LW	Group C - Temperate	(Cfb)	Oceanic

Surveys (n=4,655) were carried out between June 1997 and October 1998. Concurrently to environmental monitoring, transverse questionnaires (at a single point in time) were completed, which applied questions on indoor environmental perception and preference, self-assessed productivity, use of environmental controls, clothing and activity level. This questionnaire was answered several times by the same participants in different seasons. For the purposes of this paper the results of three questions are analysed, including thermal perception (7-point scale), thermal preference (5-point scale) and overall comfort sensation (6-point scale).

The analysis method relies upon an unpaired sample, therefore the first step was to ensure independence of the data; i.e. each participant had only one observation which could have been completed during any season. Only the results of the first survey were retained for each participant (n=785). MW buildings were removed from the sample, the final sample size was n=451. Then the results of the three questions were transformed into binary variables (see Table 2). With regard to thermal sensation, 'neutral' was presumed to be the desired thermal sensation, which is the case conventionally and has also been shown to be the "*commonest personal desired*" sensation (Humphreys, 2007).

Table 2. Coding the scales of warmth, preference and comfort

Code	**Thermal sensation** *How do you feel?*	**Thermal preference** *How would you prefer to feel?*
0	Hot Warm Slightly warm	Much cooler A bit cooler
1	Neutral	No change
0	Slightly cool Cool Cold	A bit warmer Much warmer

Code	**Overall comfort sensation** *How would you rate your overall comfort?*
1	Very comfortable Moderately comfortable Slightly comfortable
0	Slightly uncomfortable Moderately uncomfortable Very uncomfortable

The analysis applies methods for categorical variables by reviewing the number of occurrences that fall into each combination of categories. The first part of the analysis reviews the distribution of thermal perception, thermal preference and overall comfort sensation for both HW and LW buildings. The second part of the analysis explores the relationship between two categorical variables (see Figure 1 Part A) using Pearson's chi-square test with Yate's continuity correction to avoid Type I error (identifying an effect that is not present). Finally the third part of the analysis explores the relationship between three categorical variables (see Figure 1 Part A and B) requiring a log linear analysis.

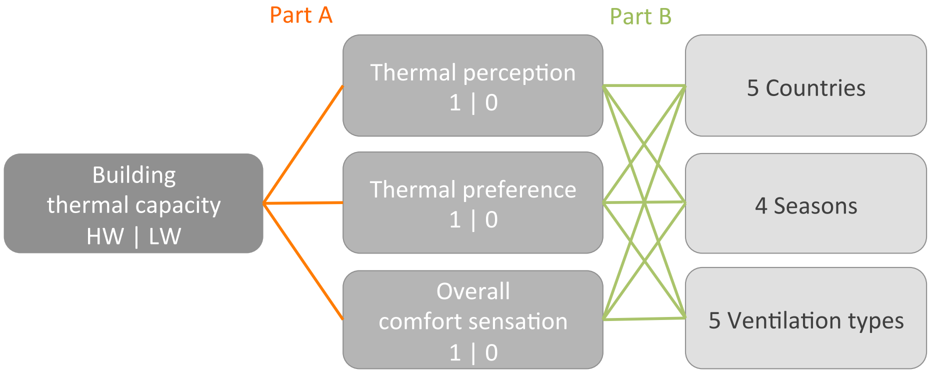

Figure 1. Map of the variables and relationships reviewed in this study.

Results

The analysis explores participants' reported thermal perception (Tperc), thermal preference (Tperf) and overall comfort sensation (comfort). Interestingly at the time of the surveys, indoor air temperature in HW buildings (median=24.1°C) and in LW buildings (median=23.8°C) did not differ significantly, W=23655, p=0.60. Furthermore the daily mean external temperature of HW buildings (mean=14.10°C, sd=5.70°C) and of LW buildings (mean=13.3°C, sd=4.9°C) did not differ significantly either, t(240.7)=1.5, p=0.14.

Thermal perception

Figure 2 shows that more participants reported to be thermally neutral in HW buildings (41%) than in LW buildings (32%); while more participants reported feeling cold, cool, slightly cool, slightly warm, warm and hot in LW buildings (68%) than in HW buildings (59%).

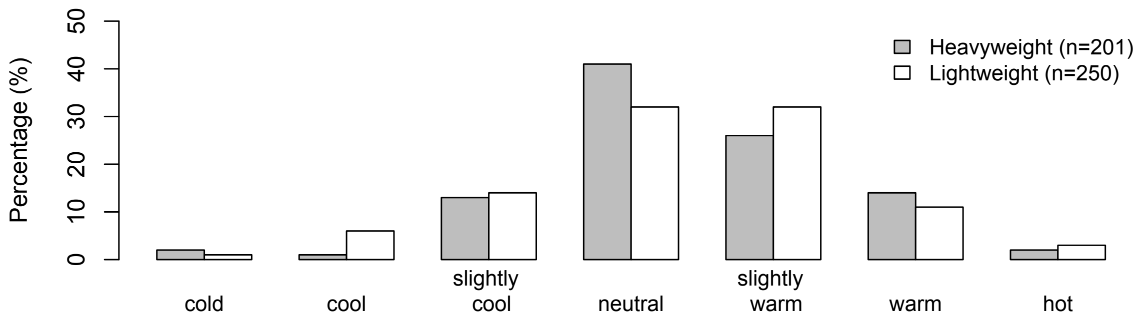

Figure 2. Distributions of thermal perception results for heavy and lightweight buildings.

Results of the first analysis show that there was a significant association between a building's thermal capacity and whether or not participants felt neutral, $\chi^2(1)=3.78$, p=0.05. This seems to represent the fact that based on the odds ratio, the odds of a participant feeling thermally neutral were 1.5 (95% confidence interval: 1, 2.24) times higher if they were in a HW building than if they were in a LW building.

The three-way log linear analyses produced final models that include the interaction (capacity:Tperc:country), but dismiss the interactions (capacity:Tperc:season) and (capacity:Tperc: ventilation type). To breakdown these effects, separate chi-square tests on 'capacity' and 'Tperc' variables were performed separately for each country, season and ventilation type. The sample for Greece did not have any LW buildings; therefore the analysis could not be completed. For Sweden and the UK (oceanic climates), there was no significant association between buildings thermal capacity and thermal perception; however for Portugal and France there was a significant association, respectively $\chi^2(1)= 9.55$, $p<0.05$ and $\chi^2(1)=5.1$, $p<0.05$. In Portugal, the odds of a participant feeling neutral were 6.86 times higher if they were in a HW building than if they were in a LW building. In contrast, in France, the odds of a participant feeling neutral were 3.89 times higher if they were in a LW building than if they were in a HW building. This result for France might be influenced by the different ventilation strategies applied in LW building (MV) and HW buildings (NV and MV). To review this potential effect, a subset of buildings with the same ventilation strategy (MV) for France was reviewed (see Figure 3). In this instance, results of the analysis of this subset (MV) shows that there was no significant association between buildings thermal capacity and whether or not participants felt neutral, $\chi^2(1)=2.22$, $p=0.14$.

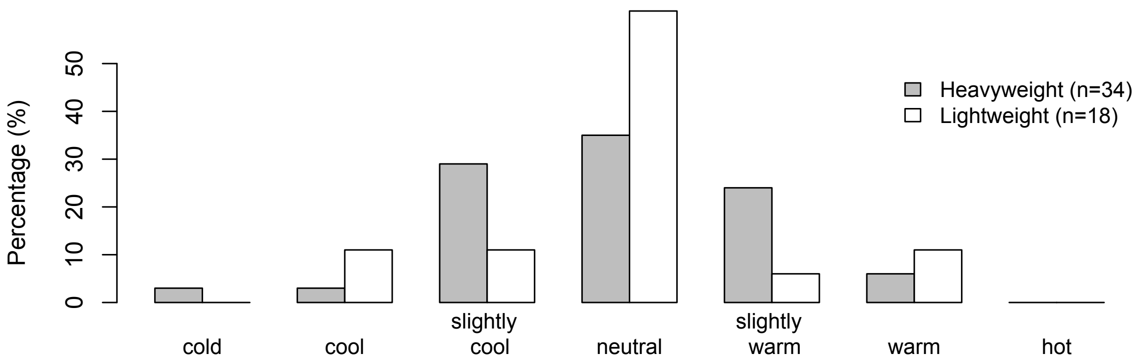

Figure 3. Distributions of thermal perception results for heavy and lightweight MV buildings in France.

For the four seasons, there was no significant association between buildings thermal capacity and thermal perception. The sample for (*AC*) and (*MM*) ventilation types did not have any HW building; therefore the analysis could not be completed. For (*MV*) and (*PP*), there was no significant association between buildings thermal capacity and thermal perception; however for (*NV*) there was a significant association, $\chi^2(1)= 3.86$, $p<0.05$. Based on the odds ratio, the odds of a participant feeling neutral were 2.12 times higher if they were in a HW building than if they were in a LW building. To conclude there was a difference between ventilation types and countries but no difference between seasons.

Thermal preference

Figure 4 shows that slightly more participants preferred no thermal change in HW buildings (46%) than in LW buildings (43%), and more participants preferred cooler and warmer conditions in LW buildings.

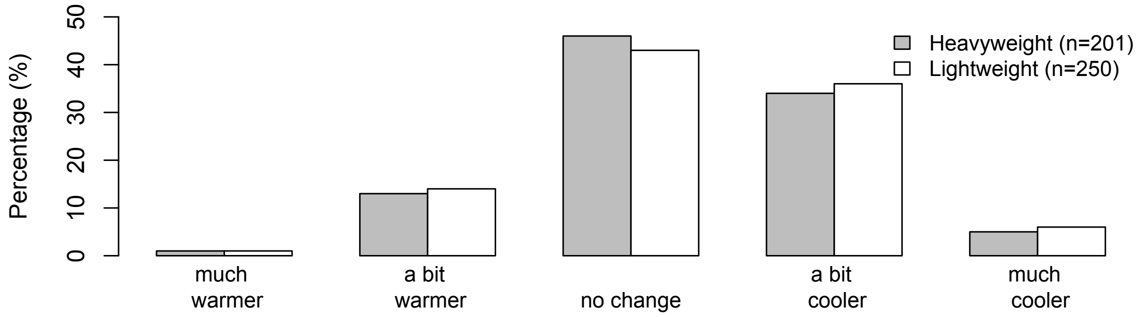

Figure 4. Distributions of thermal preference results for heavy and lightweight buildings.

Results of the analysis show that there was no significant association between buildings thermal capacity and whether or not participants wanted a change in thermal conditions, $\chi^2(1)=0.31$, $p=0.58$.

Overall comfort sensation

Figure 5 shows that more participants felt comfortable in HW buildings (68%) than in LW buildings (58%), while more participants felt uncomfortable in LW buildings (42%) than HW buildings (32%).

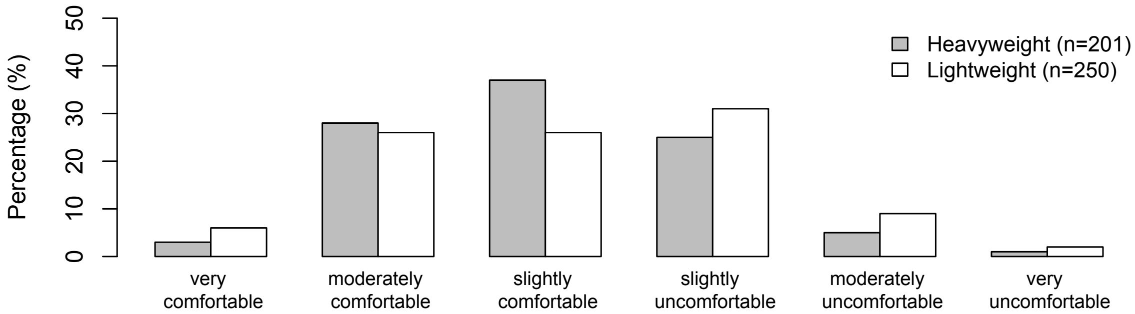

Figure 5. Distributions of overall comfort sensation results for heavy and lightweight buildings.

Results of the analysis show that there was a significant association between a building's thermal capacity and whether or not participants felt comfortable, $\chi^2(1)=4.37$, $p<0.05$. This seems to represent the fact that based on the odds ratio, the odds of a participant feeling comfortable were 1.5 times higher if they were in a HW building than if they were in a LW building.

The three-way log linear analyses produced a final model that dismissed the interactions (capacity:comfort:country), (capacity:comfort:season) and (capacity:comfort: ventilation type). To breakdown these effects, separate chi-square tests on 'capacity' and 'comfort' variables were performed separately for each country, season and ventilation type. The sample for Greece did not have any LW buildings; therefore the analysis could not be completed. For the other four countries, there was no significant association between a building's thermal capacity and overall comfort sensation. For the four seasons, there was no significant association between a building's thermal capacity and overall comfort sensation. The sample for (*AC*) and (*MM*) ventilation types did not have any HW buildings; therefore the analysis could not be completed. For (*MV*) and (*PP*), there was no significant association between a building's thermal capacity and overall comfort sensation; however for (*NV*) there was a significant association, $\chi^2(1)=3.98$, $p<0.05$. Based on the odds ratio, the odds of a participant feeling comfortable were 2 times higher if they were in a HW building than if they were in a LW building. To conclude there was a difference between ventilation types but no difference between countries or seasons.

Conclusions

Results show significant relationships between building thermal capacity and thermal perception, and between building thermal capacity and overall comfort sensation. However there was no relationship between building thermal capacity and thermal preference. If a participant was feeling warm or cool, he/she will want a change in thermal environment irrespective of the building thermal capacity. To answer the research question, heavyweight buildings were reported to be more comfortable than lightweight buildings. The odds of a participant feeling thermally neutral or comfortable were both 1.5 times higher in HW buildings than LW buildings.

To address the first hypothesis, thermal perception and overall comfort were reviewed across all four seasons. Results show that thermal capacity does not seem to have an effect on thermal perception and overall comfort sensation for all four seasons. This insight goes against the first hypothesis that thermal capacity may alleviate discomfort in summer. This unexpected result may be due to the ventilation strategies considered in this study. Thermal mass can have a negative effect of keeping a building warm at night, and therefore thermal mass needs to be combined with night ventilation to dissipate the heat stored during the day (Hacker, 2005). With regard to the second hypothesis, different ventilation types were reviewed. Thermal capacity does not seem to have an effect for MV and PP buildings. However in NV buildings, participants reported to be more thermally neutral and comfortable in HW buildings than in LW buildings. This insight confirms the second hypothesis; a naturally ventilated building, where internal temperature are likely to be less tightly controlled, should have high thermal mass to alleviate potential thermal discomfort. Finally different countries were reviewed. Thermal capacity does not seem to have an effect in oceanic and humid climates. However in Mediterranean climates, participants were more likely to report being thermally neutral in HW buildings. This insight could be particularly useful in the choice of building design as temperatures are set to rise across Europe in near future.

In this study, the thermal capacity of the case-study buildings is identified at an aggregated building level. This is a limitation of the study, as the relationship to be reviewed should be occupants' comfort versus the available heat capacity of the internal surfaces, walls, floors, ceilings and furniture to the occupants are exposed to. This may or may not correspond to the aggregated thermal capacity of the building. Furthermore, the interactions between internal thermal capacity, solar gains and ventilation may be reviewed; in particular where thermal mass is located to best capture solar radiation and to enable convective heat released from materials. Future empirical and modelling studies may review in which building elements is thermal mass most effective in providing a comfortable environment.

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