Nudging the Adaptive Thermal Comfort Model

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Abstract

The release of the largest database of thermal comfort field studies presents an opportunity to perform a quality assurance exercise on the first generation adaptive comfort standards (ASHRAE 55 and EN15251). The analytical procedure used to develop the ASHRAE 55 adaptive standard was replicated on 60,321 comfort questionnaire records with accompanying measurement data. Results validated the standard's current adaptive comfort model for naturally ventilated buildings, while suggesting several potential nudges relating to the adaptive comfort standards, adaptive comfort theory, and building operational strategies. Adaptive comfort effects were observed in all regions represented in the new global database, but the neutral temperatures in the Asian subset trended 1-2 °C higher than in Western countries. Moreover, sufficient data allowed the development of an adaptive model for mixed-mode buildings that closely aligned to the naturally ventilated counterpart. We present evidence that adaptive comfort processes are relevant to the occupants of all buildings, including those that are air conditioned, as the thermal environmental exposures driving adaptation occur indoors where we spend most of our time. This affords significant opportunity to transition air conditioning practice into the adaptive framework by programming synoptic- and seasonal-scale set-point nudging into building automation systems.

Keywords

adaptive thermal comfort; HVAC; mixed-mode; natural ventilation; energy; standards; climate

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Highlights

- A large thermal comfort database validated the ASHRAE 55-2017 adaptive model
- Adaptive comfort is driven more by exposure to indoor climate, than outdoors
- Air movement and clothing account for approximately 1/3 of the adaptive effect
- Analyses supports the applicability of adaptive standards to mixed-mode buildings
- Air conditioning practice should implement adaptive comfort in dynamic AC setpoints

1. Introduction

The provision of thermal comfort for building occupants stands out as one of the largest end-uses of energy in the built environment, bearing significant responsibility for greenhouse gas emissions and their destabilizing effects on our global climate system (Lucon et al., 2014; Berardi, 2017). One of the more common architectural answers to these challenges is climate-responsive or passive design of buildings, where natural ventilation is substituted for mechanical conditioning to deliver comfortable indoor environments while at the same time zeroing energy demand for heating, ventilation, and air-conditioning (HVAC). Where external climatic conditions or the building program are not amenable to exclusive reliance on natural ventilation, the hybrid approach known as mixed-mode (i.e., a combination of operable windows and mechanical conditioning) represents an alternative low-energy design strategy. By forestalling the onset of mechanical conditioning for as long as outdoor weather conditions permit, a mixed-mode design minimizes HVAC energy demand without compromising occupant thermal comfort. Successful implementation of a mixed-mode strategy includes a relaxation of the conventionally tight deadband between heating and cooling setpoints. Figure 1 shows reductions in annual HVAC-energy consumption of roughly 7-15% for every degree Celsius expansion in either direction beyond a temperature control dead-band of about 2 K (Hoyt et al., 2015). Utilizing natural ventilation is one mechanism for maintaining comfort within those wider temperature ranges. Significant energy savings can therefore be achieved through an operational change as simple as nudging setpoint temperatures (Ghahramani et al., 2016).

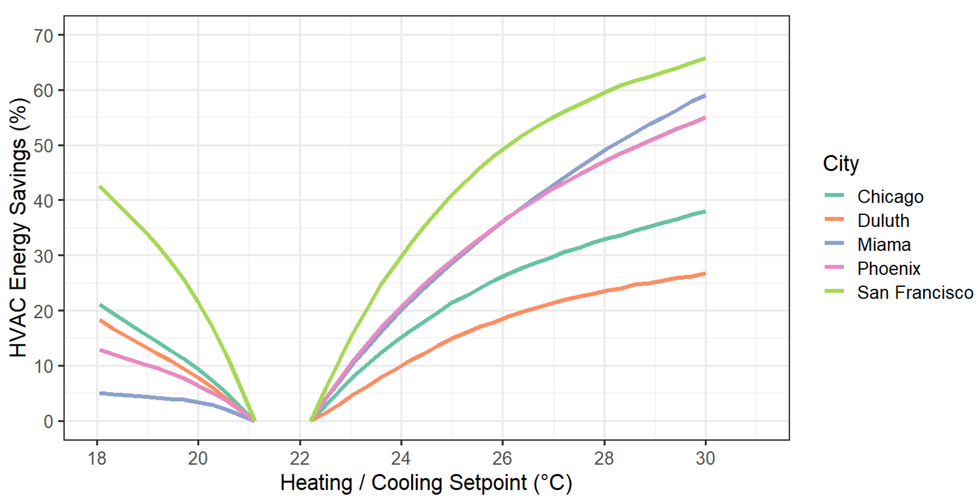

Figure 1. The potential HVAC energy savings associated with widened heating and cooling setpoints for a standardized grade-A reference office building in three American cities with diverse climates. Modified after Hoyt et al. (2015).

Challenging conventional comfort theory and practice of the time, de Dear and Brager (1998) and Nicol & Humphreys (2002) proposed adaptive comfort models as the appropriate tool for designing naturally ventilated spaces and quantifying their operational comfort performance. In the two decades since then, practitioners have applied the adaptive comfort approach to the design and operation of many naturally ventilated buildings. And comfort researchers have tested the model with thousands of new *right-here-right-now* comfort data points from buildings scattered across diverse climate zones around the world (de Dear et al., 2013). But the needle is not moving fast enough in the promotion of climate-responsive designs with minimal reliance on air-conditioning to abate greenhouse gas emissions from the built environment. In *The Healthy Workplace Nudge*, Miller *et al*. (2018) borrow ideas from Thaler & Sunstein (2008) and use behavioral economics to discuss how “nudge thinking” allows small, positive unobtrusive changes to promote healthy decisions. With this in mind, this paper aims to nudge the adaptive thermal comfort model to increase robustness and incrementally expand its scope of applicability for use in building design and operation in the hope that this will lead to improved energy and comfort performance.

1.1 Changing landscape of adaptive thermal comfort

Based on the pioneering framework of thermal comfort by Nicol & Humphreys (1973), de Dear and Brager’s adaptive comfort model (1998) was first codified by ASHRAE in 2004 (ASHRAE 55-2004). It has since been replicated in other jurisdictions, notably the European Union (EN15251), and more recently in China (Li et al., 2014) and India (Manu et al., 2016). The model’s name references a view of building occupants as active agents in the achievement of thermal comfort. This idea marked a sharp departure from the orthodox thermal comfort view of occupants as passive recipients of their immediate physical environment (Fanger, 1970). By debunking the conventional assumption that thermal comfort could only be achieved within a narrow band of indoor temperatures, the adaptive comfort model and derivative standards conferred legitimacy on passive and low energy design strategies focused on natural ventilation.

The 1998 and 2002 publications proposing adaptive comfort standards sparked a flurry of new research activity on the topic. We conducted a bibliometric analysis using the Scopus database to understand the impact of the adaptive concept on the thermal comfort research domain in recent decades. A query of journal papers and conference proceedings with titles, abstracts, or keywords containing the words ‘adaptive’ AND ‘thermal’ AND ‘comfort’ returned a total of 1,200 documents in April 2019. Figure 2 presents these research publication events as a time series demonstrating the growth in outputs in the last 20 years. Whilst traditional centers of thermal comfort research – UK, USA, Italy, Germany and Australia – appear on the list of productive countries, relative newcomers, including China, India, and Hong Kong are becoming increasingly prominent. Our analysis showed China currently ranked the second most productive country behind the UK, and if the current trajectory is maintained, it is poised to become number one in the near future. The important takeaway is that the center of gravity of adaptive comfort thinking is shifting from places like UK, USA, and Europe towards emergent research hubs in Asia.

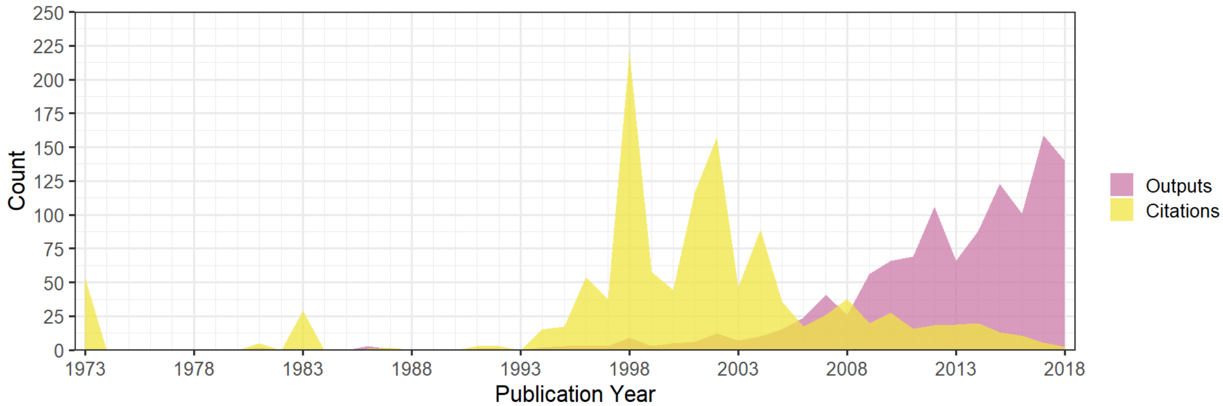

Figure 2. The number of research outputs and citations by year since the first paper on adaptive comfort by Nicol & Humphreys in 1973. Citation count refers to the year in which the cited paper was published.

Increased research activity in Asian countries has been accompanied by efforts to localize adaptive models in increasingly specific contexts. Whilst the general adaptive principle has been repeatedly demonstrated across diverse settings, region-specific adaptive models are not universally applicable. ASHRAE's Standard 55 adaptive comfort model and the European Union counterpart of EN15251 were transformative because of their generalizability, the empirical basis of which was vastly more comprehensive than anything preceding them. But in the two decades since their endorsement, there has been a large number of thermal comfort field studies in unique contexts. The recently-released ASHRAE Global Thermal Comfort Database II (Földváry Ličina et al., 2018a), with over 100,000 rows of "*right-here-right-now*" thermal comfort field data from around the world, is an order of magnitude larger than its predecessor that was used to develop the ASHRAE Standard 55 adaptive comfort model (de Dear, 1998). It is beyond the scope of the present paper to summarize the database, but a detailed description can be found in Földváry Ličina et al. (2018b).

1.2 Research aims

In light of the changing landscape of adaptive thermal comfort research over the last two decades, and the release of the ASHRAE Global Thermal Comfort Database II - referred to hereafter simply as Database II - into the public domain, a follow-up analysis of the adaptive concept seems timely. The availability of a large volume of new data from diverse climatic and regional contexts provides an opportunity to revisit the original ASHRAE 55 adaptive comfort standard. In the interests of nudging our current understanding of adaptive theory, the existing adaptive comfort model, and the application of adaptive principles to building operational strategies, our principal aims for this paper are as follows:

1. Replicate the analysis by de Dear & Brager (1998) on a larger and more representative dataset to validate the original adaptive comfort model,
2. Assess differences in adaptive comfort principles across broad regions of the world,
3. Propose revisions to extend the limits of applicability of the adaptive comfort model beyond naturally ventilated buildings as currently specified in ASHRAE Standard 55-2017,
4. Discuss the potential to nudge HVAC practices to incorporate adaptive comfort theory as an energy-reduction strategy.

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2. Method

Our analysis of Database II was designed to intentionally replicate the development procedure of the previous ASHRAE adaptive comfort model to ensure backwards compatibility with associated standards. We used “R” (R Core Team, 2019) and the “RStudio IDE” (Rstudio Team, 2018) along with the following packages: tidyverse (Wickham, 2017), data.table (Dowle & Srinivasan, 2019), bibliometrix (Aria & Cuccurullo, 2017), comf (Schweiker et al., 2019), ggpmisc (Aphalo, 2016), here (Müller, 2017), countrycode (Arel-Bundock et al., 2018), rworldmap (South, 2011), climateeng (Rasmussen, 2016), and grateful (Rodriguez-Sanchez, 2018). Relevant data visualizations are grouped by conditioning strategy - air conditioned (AC) in black, mixed-mode (MM) in mustard, and naturally ventilated (NV) in blue.

2.1 Modified ASHRAE Database II

We made some modifications to the public domain version of Database II in order to perform the analyses required for this paper. The timestamps of measurements were retrospectively added by referring back to the original publications stemming from contributed datasets. These included the month and year of the study as a minimum, with 50,287 timestamps retrieved. This allowed us to attach more temporally specific meteorological data to those records than the climatological averages currently in the online version of Database II. Specific monthly temperatures for the closest meteorological station were extracted from the Global Historical Climatology Network-Monthly (GHCN) database, a public resource compiled by the National Oceanic and Atmospheric Administration (Trouet & Van Oldenborgh, 2013). Our revisions to the meteorological data in Database II were based on the following priorities: original data from database contributor were preferred (59,995 records), but if not available the data from GHCN database was substituted (19,995 records), and if neither of these options were available, we resorted to historical climatic averages (27,593 records). This included daily temperature measurements from ASHRAE Database I (the basis of the current ASHRAE adaptive comfort standard), which were also supplemented with monthly meteorological data for those records where available.

Unlike its predecessor, Database II does not explicitly identify building level metadata. As a result, directly replicating the analysis in the original ASHRAE Standard 55 adaptive comfort model was initially impossible with Database II because the estimation of thermal neutralities using the linear regression method (de Dear 1998) was based on the individual building as the unit of analysis. To address this we used simple heuristics to infer building identification numbers (referred to as building ID in this analysis) across Database II by determining unique cases based on publication, city, conditioning strategy, and season (summer and winter were collapsed to include autumn and spring respectively, merely for this purpose). Such backfilling of meteorological data and building ID codes were necessary prerequisites to replicating the analytical strategy used to define the ASHRAE adaptive comfort model.

2.2 Data analysis

The analysis by de Dear & Brager (1998) underpinning the original adaptive comfort model was based on field measurements of indoor operative temperature. This was preferred at the time as it was deemed more representative of the actual conditions experienced by building occupants through its consideration of both radiative and convective heat transfers. However, an analysis of Database II by Dawe et al. (forthcoming) determined the median absolute difference between indoor air and radiant temperature measurements as 0.4°C, meaning an even smaller difference in operative temperature. Our own exploratory analysis of adaptive comfort using Database II showed very similar results when using either air or operative temperatures. We also observed that Database II had 26,700 records missing an operative temperature value. Therefore, we used air temperature as the independent variable in the following analyses to enable us to access the statistical power of the complete database.

The analytical precedent of the ASHRAE Standard 55 adaptive comfort model was replicated here on a subset of the modified Database II containing all records from office buildings having concurrent observations of indoor air temperature, thermal sensation vote, and outdoor mean monthly temperature. The resulting subset contained 60,321 records from a total of 135 inferred buildings, including 15,203 records from the original Database I. We calculated coefficients based on the sample size from each building ID and used them to weight the regression analyses. Fifty six percent of the sample was from Summer (or Autumn) and the remaining from Winter (or Spring). A map showing the countries and sample size of the field studies comprising the subset database is shown in Figure 3.

Following the ASHRAE Standard 55 adaptive model's precedent we performed a simple linear regression to predict thermal sensation vote (ASHRAE 7-point scale) based on binned indoor air temperature measurements (0.5°C intervals) with building ID as the unit of analysis. Twenty eight regression models failed to reach statistical significance ($p \geq 0.05$), resulting in linear models for 107 of the 135 building IDs. The neutral temperature for those building IDs could have been determined using the Griffiths method but that method has recently been shown to vary significantly between different contexts (Rupp et al., 2019). The statistically insignificant models only accounted for 4% of the dataset and were therefore dropped from the analysis. We determined a neutral temperature for each building ID based on a backwards solution of its regression model for neutral thermal sensation votes (TSV = 0). Fifteen buildings with mean outdoor monthly temperature below 10°C or above 33.5°C did not significantly change the regression models and were ultimately dropped from the analysis as they fall beyond the limits of the original adaptive model.

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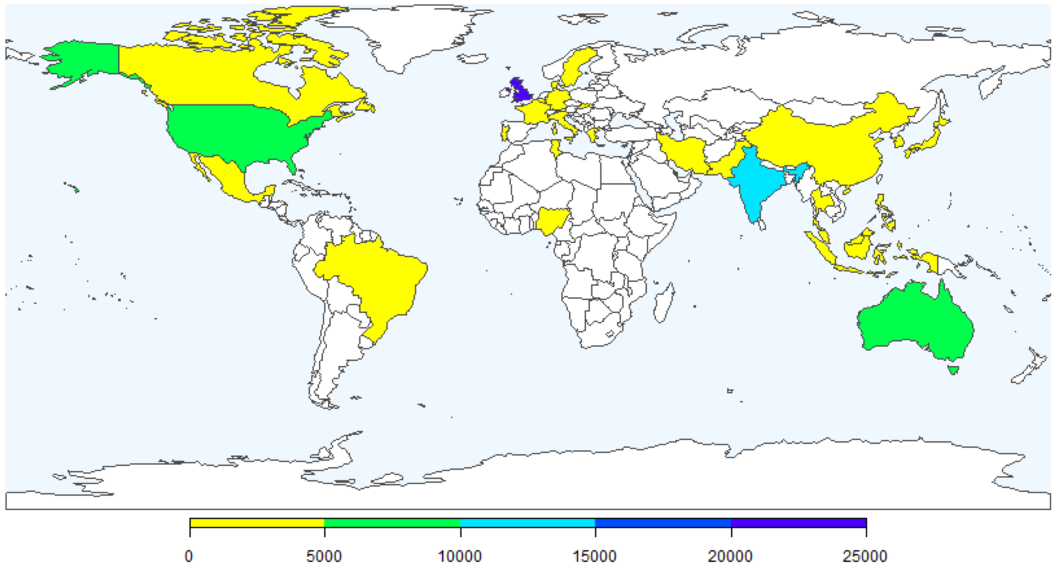

Figure 3. World map showing the sample size by country in the subsetted database in in our analysis. The UK has the largest contribution, but there is broad representation from countries throughout Asia in Database II.

3. Results

The first part of this section reports on the analysis of the subsetted Database II following the methods of de Dear & Brager (1998) to verify the ASHRAE Standard 55 adaptive comfort model, and explores several potential nudges. The second part is based on neutral temperatures determined using the Standard Effective Temperature (SET) index instead of air temperature, as SET accounts for the six basic parameters in the human heat balance (t_a, t_r, *RH, v, clo, met*). The SET analysis includes detailed descriptions of the indoor physical environmental conditions prevailing at the time the comfort questionnaires were administered, and allows us to explore the differences between adaptive comfort models obtained from buildings with different conditioning strategies, and further nudge our understanding of the underlying mechanisms of adaptation.

3.1 Adaptive thermal comfort model

The results of the weighted least square regression in Figure 4 shows the relationship between the neutral temperatures and mean monthly outdoor temperature for each building classified according to its conditioning strategy. It is the same data visualization used in the ASHRAE Standard 55 adaptive comfort model analysis. The differences between conditioning strategies are comparable to those found by de Dear & Brager (1998) on the smaller Database I (~21,000 records), while also revealing new patterns that are described in subsequent sections.

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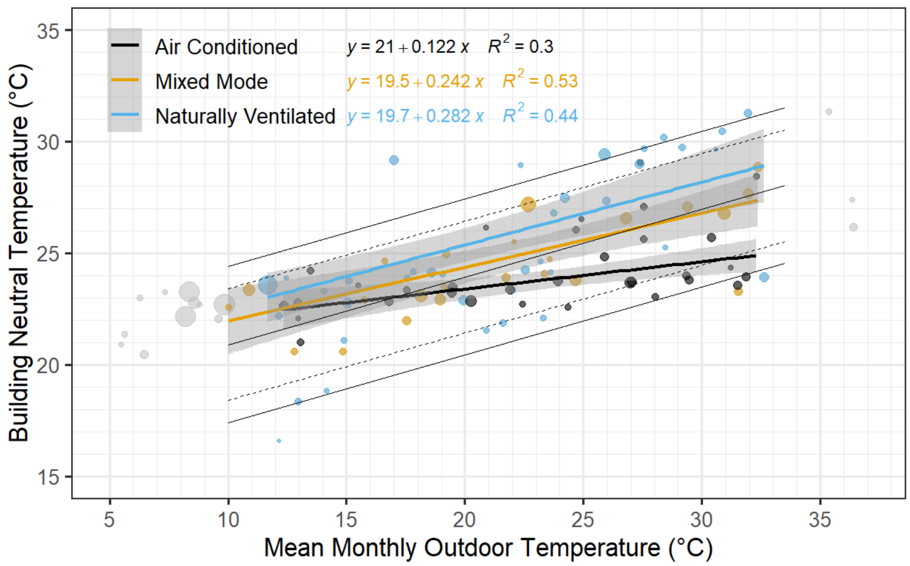

Figure 4. Neutral temperatures of buildings (determined using the same neutrality regression method as de Dear & Brager 1998) and the mean monthly temperature prevailing during each building's comfort survey. Each point shows an individual inferred building ID, and the point size is proportional to the weighting coefficient (sample size) attached to that building ID when fitting the regression model. The colors of the regression lines and model coefficients indicate the conditioning strategy of the building. The grey shading marks the 95% confidence interval around the fitted models. Light grey points are those buildings falling outside the original ASHRAE model's outdoor temperature domain (10, 33.5) that have been excluded from the regression analysis after confirming they didn't make a difference. The original ASHRAE Standard 55 adaptive model plus its associated 80% and 90% acceptability limits for NV buildings are superimposed for reference. Models for AC ($R^2 = 0.31$, $F(1,30) = 12.61$, $p < 0.01$), MM ($R^2 = 0.53$, $F(1,21) = 23.94$, $p < 0.0001$), and NV ($R^2 = 0.44$, $F(1,35) = 27.47$, $p < 0.00001$) were all highly significant.

3.1.1 Naturally ventilated buildings

Starting the analysis with naturally ventilated buildings (NV) is logical given they are the focus of the ASHRAE Standard 55 adaptive comfort model. The slope of the regression for NV buildings in Database II is 0.28 $^{o}C^{-1}$, comparable to that of the original ASHRAE Standard 55 adaptive comfort model (0.31 $^{o}C^{-1}$). The Y-intercept term of the Database II NV regression model at 19.7°C is 2.1°C higher than its counterpart in the original adaptive model for NV buildings (17.8°C), and 1°C warmer than the value found in the EN15251 adaptive model which was based on an exclusively European database.

We questioned whether the higher offset of the Y-intercept in the Database II NV model might be the influence of broader regional representation following the inclusion of measurements from countries new to the larger dataset. To investigate this, we repeated the same analysis but on separate Western (Europe, North America, Australia) and Asian (Middle-East, Indian subcontinent, and South, Southeast, and East Asia) subsets. Building IDs from Africa (n = 7) and South America (n = 3) were excluded from this specific analysis because of insufficient data to perform regressions for those regions. Figure 5 shows that both indoor and outdoor temperatures are generally higher in the Asian subset compared to Western, resulting in a higher concentration of data points in the top-right quadrant of the graph. For comparable outdoor climates in both regions, the neutral temperatures in both NV and AC buildings in the Asian subset trended slightly higher by a degree or two compared to their counterparts in the Western subset. And since this is occurring in *both* NV and AC buildings, it cannot entirely be explained by adaptation that is isolated to free-running NV buildings (this will be discussed later). The spread of neutral temperatures in Figure 5 suggest that the warmer indoor and outdoor temperatures from field studies in Asian cities in Database II may have driven much of the warmer displacement of the Y-intercept term for the model reported in Figure 4 from the original coefficients reported by de Dear & Brager (1998).

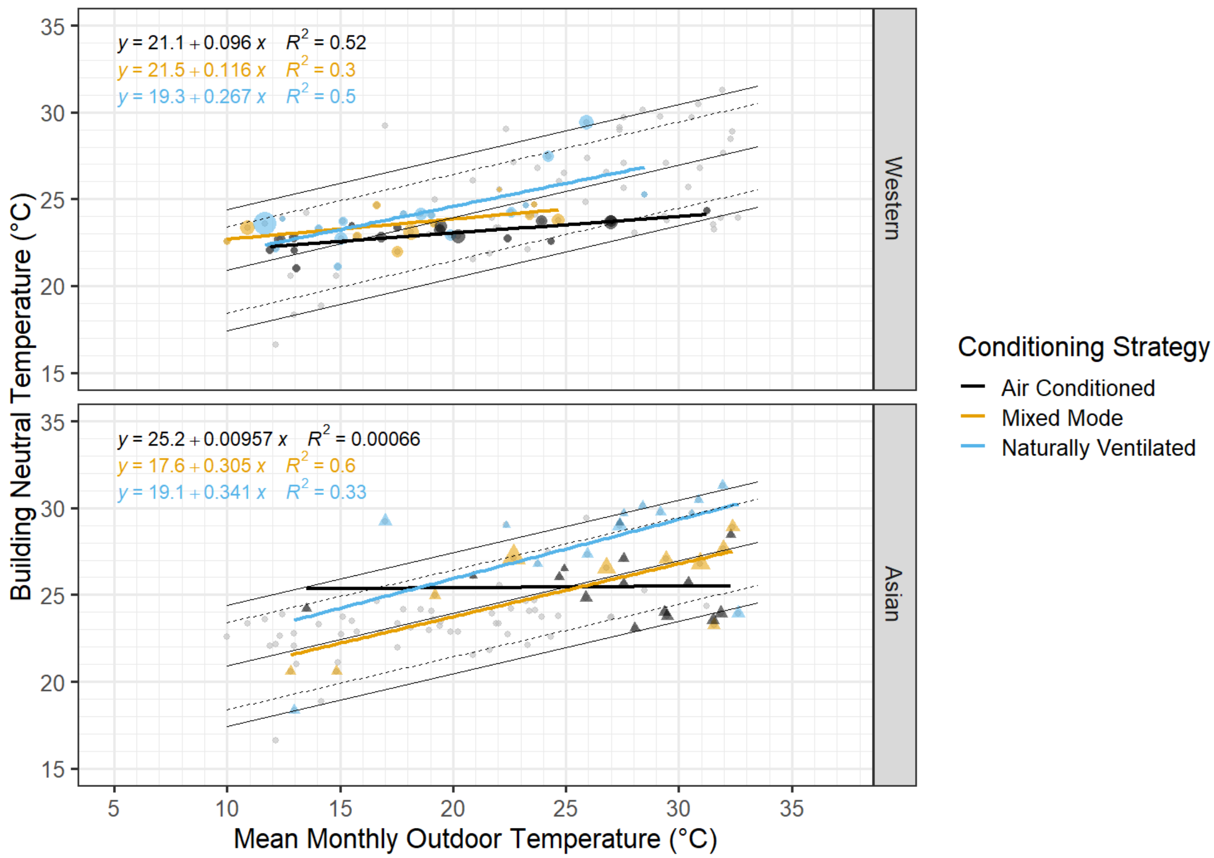

Figure 5. Neutral temperatures of buildings and the prevailing mean monthly temperature for buildings in Western (top) and Asian (bottom) countries. The colors of the unweighted regression lines and model coefficients indicate the conditioning strategy of the building. The symbol shape indicates the subset (circle = Western, Triangle = Asian). Grey points represent buildings from the other subsets to aid comparison. The original ASHRAE Standard 55 adaptive model for NV buildings is superimposed for reference. Models statistics in the Western subset for AC (R^2 = 0.52, $F(1,14)$ = 19.54, $p < 0.001$), MM (R^2 = 0.30, $F(1,9)$ = 1.123, p = 0.32), and NV (R^2 = 0.50, $F(1,14)$ = 23.08, $p <$ 0.001) and the Asian subset for AC (R^2 = 0.00, $F(1,13)$ = 0.06, p = 0.81), MM (R^2 = 0.60, $F(1,8)$ = 3.25, p = 0.11) and NV (R^2 = 0.33, $F(1,12)$ = 1.664, p = 0.22) show only two of the regressions are significant.

3.1.2 Mixed-mode buildings

Neither ASHRAE's adaptive comfort model nor the European EN15251 version had sufficient field study data from mixed mode buildings (MM) to sustain any meaningful adaptive model regression analyses. But the current subset from Database II contains 25 separate MM buildings scattered across sufficiently diverse climatic zones to produce a statistically significant adaptive comfort model shown in Figure 4. As anticipated, the MM regression line falls between the NV and AC adaptive comfort models reported in that figure, but is more closely aligned to NV than AC. This finding supports the notion that well-designed mixed-mode buildings should

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operate first as naturally ventilated buildings when and where possible, and use air conditioning to temper weather extremes only when necessary.

3.1.3 Air-conditioned buildings

The results reported in Figure 4 show a muted relationship between the neutral temperatures in buildings operating under AC and concurrent monthly outdoor temperatures. This is in line with the original adaptive comfort model, and our analysis by region reported in Figure 5 indicates the same pattern across climates and cultures. It is for this reason that adaptive principles have historically been discussed only in relation to highly permeable, naturally ventilated or free-running buildings, where indoor temperatures drift in the direction of prevailing weather and seasons. Conversely, indoor temperatures in air conditioned buildings were assumed to be relatively independent of outdoor climatic conditions because conventional practice is for setpoint temperatures to remain static throughout the year irrespective of trends and fluctuations outdoors. Yet many occupants typically spend much of their daily lives inside office buildings, so it is conceivable that the environments *inside* our buildings exert some influence over adaptive thermal comfort, as well as the outdoor conditions.

This line of reasoning prompted us to question whether adaptation to the thermal environment occurred for occupants of AC buildings. To test this hypothesis, we calculated the mean *indoor* air temperature using all available records for each building within the database. In many cases this comprised measurements made over a few days, typical of field study research designs. The mean indoor air temperature substituted mean monthly outdoor temperature as the independent variable (x-axis) in the weighted least squares regression. The resulting models shown in Figure 6 indicate a much stronger statistical relationship (R^2 0.96~0.98) between the neutral temperature of a building and its mean indoor air temperature than was found when using the outdoor temperature as the independent variable (R^2 0.31~0.53). The neutral temperature for a group of building occupants is generally close to the mean indoor temperature measured inside their building. Furthermore, there were negligible differences in the relationship between conditioning strategies of buildings and between Western and Asian countries. The slope of the regression is the same for AC, MM, and NV types, the only difference being that it extends to both cooler and warmer temperatures in NV buildings. It should be noted that the same trends and relationships were observed on the smaller subset of indoor operative temperatures in our exploratory analysis.

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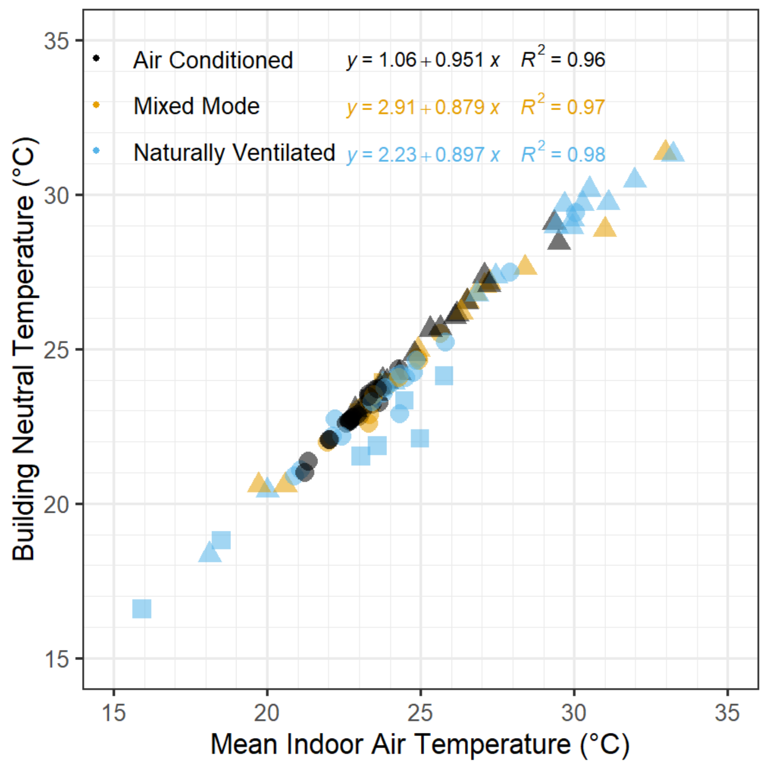

Figure 6. The neutral temperature for each building ID plotted against the mean indoor air temperature for that building. The colors of the regression lines and model coefficients indicate the conditioning strategy of the building, and show no clear difference between AC, MM, and NV types. Symbol shape indicates the regional classification of the building (circle = Western, Triangle = Asian). Models for AC (R^2 = 0.96, F(1,30) = 1696 p < 0.00001), MM (R^2 = 0.97, F(1,21) = 713.5, p < 0.00001), and NV (R^2 = 0.98, F(1,35) = 1202, p < 0.00001) were all highly significant.

3.2 Standard Effective Temperature analysis

The preceding analysis has been conducted on thermal neutralities (comfort temperatures) that we derived by regressing thermal sensation votes on concurrent indoor air temperatures. It remains unclear if the differences between regions and building conditioning strategies we reported in Section 3.1 result from a systematic shift in the underlying adaptive perceptual processes between these categories, or the effects of other human body heat-balance parameters left unaccounted in our regression models. For example, do occupants of naturally ventilated buildings in Asia deem warmer indoor temperatures to feel neutral because of the higher air speeds typically found in their indoor climates (a physical heat-balance effect), or are their thermal perceptions and preferences being nudged by sustained exposure to warmer indoor environments? Why do adaptive comfort principles manifest so clearly in naturally ventilated and mixed-mode buildings, but are dormant or heavily attenuated in air conditioned buildings? Is it because of some adaptive displacement in comfort expectations driven by greater adaptive opportunity and a history of exposure to warmer indoor temperatures, or is it simply an artefact of different clothing patterns in buildings with different conditioning strategies in place?

To explore these questions about the underlying causal mechanisms of adaptive comfort, we used the same analytical strategy reported in Section 3.1 but substituted Standard Effective

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Temperature (SET) in place of air temperature. SET is a comprehensive comfort index based on the concept of an equivalent temperature that incorporates the six physical parameters known to affect comfort, namely air temperature, humidity, mean radiant temperature, air velocity, clothing and metabolic activity. We subset the records in Database II that had the full complement of input parameters required to calculate SET. The resulting dataset contained 46,280 observations, with 97 different building IDs yielding significant weighted least square regression models of thermal sensation votes on SET.

The following subsections step through the physical characteristics of the indoor environments of these buildings as a function of mean indoor air temperature, before synthesizing them into the final SET adaptive comfort analysis. Investigation of differences in metabolic rate has been omitted here because the near-universal use of the standard lookup table leads to reduced reliability and variability of met estimates within a population.

3.2.1 Humidity

The most common critique of the ASHRAE adaptive comfort model that we have heard since it was published two decades ago is that it fails to consider the effects of humidity on occupant comfort. This looms large in the general public's understanding of thermal comfort, particularly for those in hot and humid climate zones. Figure 7 displays the psychrometric combinations of dry-bulb temperature and humidity ratio means for each building ID in the SET subset. The majority of mean dry-bulb temperatures and humidity ratios fall within the range of 20-27°C and 0.005 - 0.015 kg/kg respectively. The 12 building IDs with an average temperature and humidity above these thresholds were located in Thailand, India, or Singapore, and only two were categorized as air conditioned. Notably, there were only three buildings in the original ASHRAE database that were above these thresholds. This could lead one to question whether the effects of high humidity in hot and humid climate zones may have been underrepresented by the original adaptive comfort model. However, all 12 of those buildings were found to have neutral temperatures above 27°C SET, which corroborates the earlier findings from Figure 6 in Section 3.1 showing the strong relationship between mean indoor air and neutral temperatures of buildings, irrespective of high humidity. The effects of relative humidity on thermal neutrality will be explicated further in the SET analysis of Section 3.2.4.

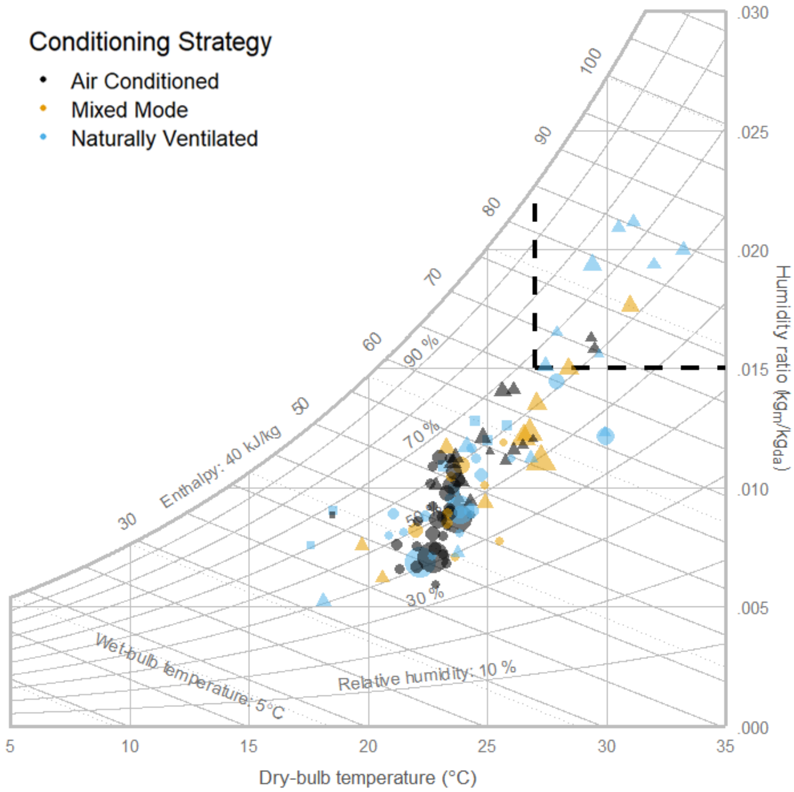

Figure 7. Psychrometric chart showing the distribution of the mean indoor temperature and humidity for each building ID. The point color indicates the conditioning strategy and the size is relative to the number of data points. The shape indicates the region; circle = Western, triangle = Asian, square = other (Tunisia).

3.2.2 Air Speed

It is assumed that one of the key indoor environmental differentiators between naturally ventilated and air conditioned buildings is that the former have higher indoor air speeds on average. This is borne out in the data shown in Figure 8. Mean indoor air speeds in AC buildings generally fell below 0.2m/s, a level widely regarded as the just perceptible draught threshold within the comfort envelope (ASHRAE Standard 55 2017 appendix I3). The four cases exceeding the 0.2 m/s average threshold were from field studies in buildings in China (Beijing) and India (Chennai) during summer. There is generally higher mean air speeds in both MM and NV building subsamples, particularly when mean air temperatures exceed 27°C. The association between indoor air temperature and air speed is stronger in the NV subsample (R^2 = 0.91) compared to the MM buildings (R^2 = 0.79).

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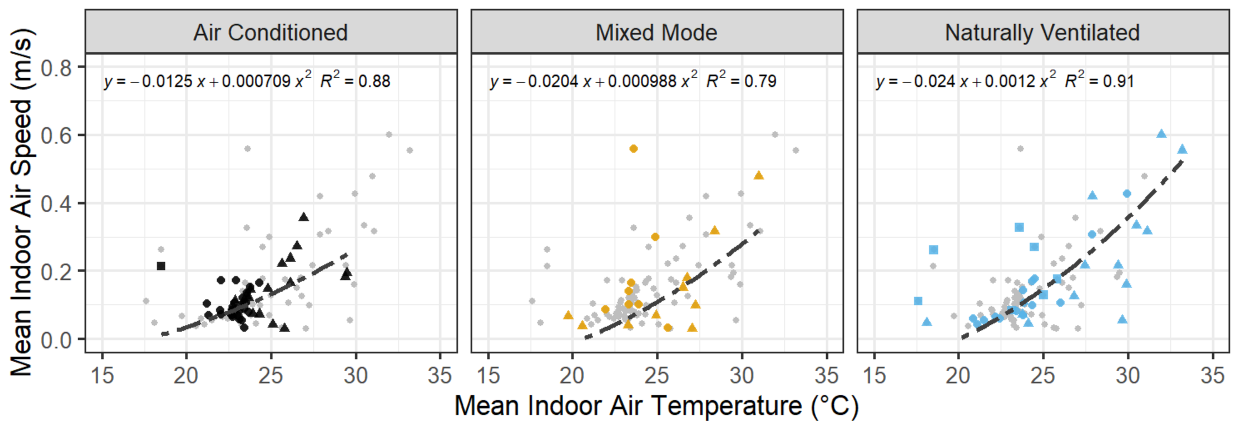

Figure 8. The mean indoor air speed for each building ID by conditioning strategy. A quadratic regression forced through the origin improved the goodness of fit for both the mixed-mode and naturally ventilated buildings over a linear model. The shape indicates the region; circle = Angle, triangle = Asia, square = other (Tunisia). Light grey dots show all data points for comparison purposes.

3.2.3 Clothing

Clothing insulation level represents the other key heat-balance parameter readily manipulated by occupants when adapting to their indoor thermal environment. The mean clothing insulation level was similar across the three building conditioning strategies (0.67 clo for AC, 0.74 clo for NV, and 0.70 clo for MM), but it's important to look beyond the mean to discover that the role played by clothing as an adaptive thermal comfort mechanism appears to be quite different. Figure 9 shows that the rate of clothing insulation decrease per degree of indoor air temperature increase was greatest for NV buildings, moderate for MM buildings, and slight for AC buildings. However, this observed statistical relationship may simply reflect the wider range of indoor temperatures (independent variable) found in MM and NV buildings.

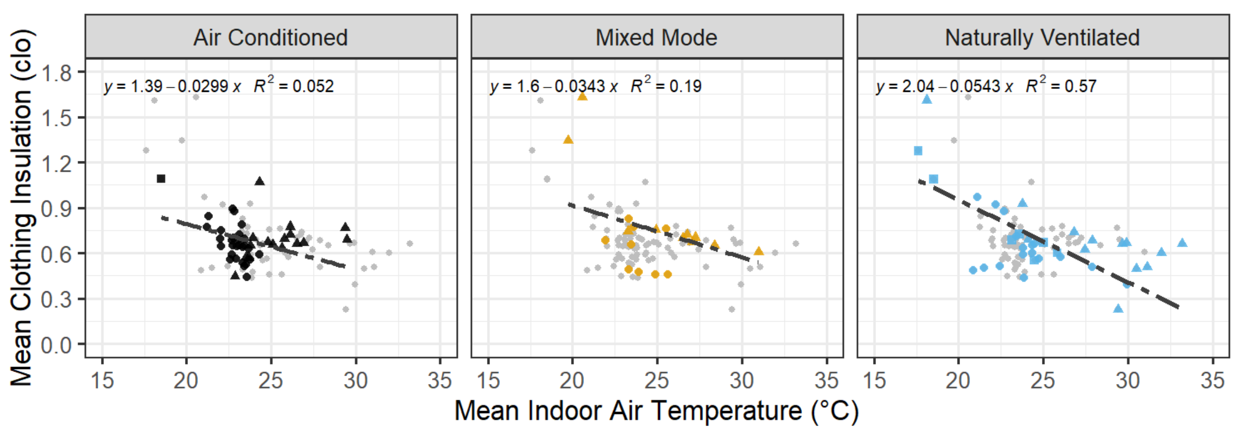

Figure 9. Mean clothing insulation level for each building ID by conditioning strategy. The shape indicates the region; circle = Angle, triangle = Asia, square = other (Tunisia). Light grey dots show all data points for comparison purposes.

3.2.4 Standard Effective Temperature

Presenting the basic heat-balance comfort parameters is helpful to characterize and differentiate the indoor environments of buildings within the database. To extend that insight and

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examine the combined comfort effects of those parameters, we repeated the adaptive comfort analysis using the SET index. That is, we regressed thermal sensation scale responses on SET rather than indoor air temperature to determine the neutral SET for each building. Figure 10 shows the relationship between the neutral SET temperatures and mean monthly outdoor temperature for each building, classified according to conditioning strategy. The focus was specifically on the three physical factors beyond temperature that are most often discussed in adaptive comfort research, namely humidity, air speed, and clothing insulation.

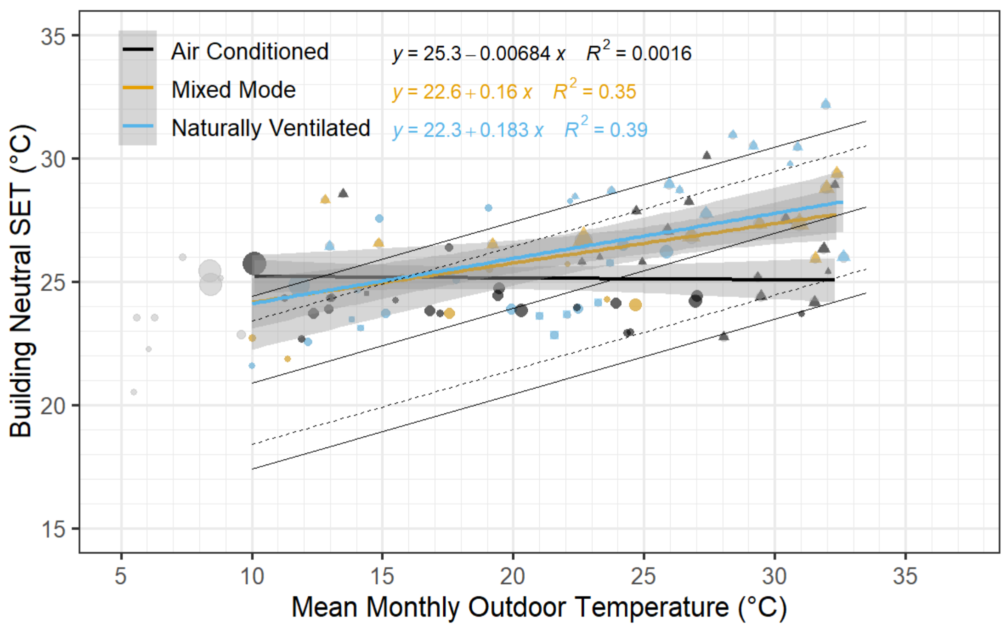

Figure 10. The same adaptive comfort model analysis as shown in Figure 4 earlier but using a subset of data with SET to establish the weighted least squares regression equation to solve for the neutral SET temperature instead of air temperature. Each point shows an individual building ID, and the point size is proportional to the weighting coefficient attached to that building ID when fitting the regression model. The colors of the regression lines and model coefficients indicate the conditioning strategy of the building. The grey shading marks the confidence interval around the fitted models. Light grey points are those buildings falling outside the original model limits (10, 33.5) that were excluded from the regression analysis after confirming they didn't make a difference. Note: the original ASHRAE Standard 55 adaptive comfort model is superimposed for reference but is not entirely accurate due to the different y-axis. The model for AC (R^2 = 0.0016, $F(1,36)$ = 0.057, p = 0.81) was not statistically significant, but those for MM (R^2 = 0.35, $F(1,16)$ = 8.44, $p < 0.01$), and NV (R^2 = 0.39, $F(1,31)$ = 20.08, $p < 0.0001$) were.

The results of the SET analysis in Figure 10 narrows the difference in the gradient or slope of the regression models between air conditioned and naturally ventilated buildings compared to the same analysis based on indoor air temperature (Figure 4). The slope coefficient of 0.18 in the SET regression equation for NV buildings is one third less than that obtained from indoor air temperature (0.28). This suggests, in effect, that approximately one third of the adaptive comfort effect can be accounted for by heat balance parameters included as inputs to the SET comfort index, notably air speed, clothing insulation, and humidity. The other portion might be attributable to factors *not* considered in the heat balance equations, such as adaptive opportunities, physiological differences, and historical patterns of variability that affect expectations and perceptions of our thermal environments. This reiterates a finding made in the original ASHRAE adaptive comfort model by de Dear and Brager (1998). A reduced regression gradient was seen for MM buildings from 0.24 to 0.16. A much higher y-intercept term was found for AC buildings when using SET.

4. Discussion

In the following section we discuss the findings of our analysis, specifically addressing the limits of applicability of the adaptive comfort model in ASHRAE Standard 55-2017. With the expanded database, we are now able to argue that the adaptive comfort principles are equally relevant to all buildings irrespective of conditioning strategy, on the basis that occupants' adaptive processes and expectations are shaped by *both* indoor and outdoor temperature exposures. This has important implications for adaptive comfort theory, the ASHRAE 55 adaptive comfort model, and the design and operation of buildings for thermal comfort. We will walk through these in the following paragraphs and propose a series of nudges in light of the present findings.

4.1 Nudging adaptive comfort theory

In naturally ventilated buildings, the relatively high permeability of the façade from operable windows means that indoor conditions are usually closely coupled to the broader outdoor climatic milieu. The use of outdoor temperature in adaptive comfort models reinforces the idea that the *outdoor* climate is the causal driver of human thermal adaptive responses. However, the weak statistical association between the comfort temperatures in air conditioned buildings and their *outdoor* temperatures reported in Section 3.1 begs the question of why outdoor climate drives comfort temperatures most strongly in naturally ventilated buildings? This question was the focus of work by Fanger & Toftum (2002) to extend the PMV model to natural ventilated buildings in warm climates, suggesting that those occupants had lower expectations of their indoor environment. It seems more likely that the typically strong correlation of indoor and outdoor temperatures in highly permeable building designs (NV and MM) means that outdoor temperature is a reasonable proxy for the fluctuations of indoor temperature. As a result, conventional adaptive models based on outdoor temperature can have high levels of predictive skill for indoor comfort temperatures, but only in climate-responsive buildings that track the natural outdoor cycles.

The overwhelming majority of our time is spent indoors, so it is conceivable that the temperatures we are exposed to *inside* the built environment exert the more powerful effect on our comfort expectations. Luo et al. (2018) showed that indoor exposure can largely shape occupants' expectations of their thermal environment. In their analysis of Database II, Cheung et al. (2019) reported better predictive capacity of thermal sensation using only indoor air temperature compared to the fully-elaborated heat-balance model (PMV-PPD) requiring six input parameters. This is far from new thinking; a very familiar graph in one of Humphreys' earliest contributions on adaptive comfort shows a compelling regression and correlation analysis (R^2 = 0.96) between mean indoor air or globe temperature and thermal neutrality observed for the building's occupants, prompting the following comment:

> *"It is interesting that such an accurate prediction can be made simply from a knowledge of the mean temperature experienced by the respondents during the observation period…the range of recent experience is better regarded as one of the factors which will contribute to the acceptability of the environment to which the respondent is exposed"* (Humphreys, 1976).

We know that indoor conditions are relatively static in air conditioned buildings, but the logical inference from our arguments in this paper (especially Figure 6 in Section 3.1.3) is that thermal adaptation occurs in *all* indoor climatic environments, regardless of conditioning strategy. The research challenge is to define the nudge of the adaptive model to account for this. The SET analysis in Section 3.2 showed that using a comprehensive heat balance comfort index to normalize the indoor environments found across conditioning strategies accounted for a significant share of the difference observed in the neutral temperature regression (comparing Figure 4 and Figure 10) between AC and NV buildings. That is to say that environmental or personal parameters in the human heat-balance equation explain about one third of the comfort temperature variability between different buildings in our analysis of Database II.

The closer alignment of the adaptive model across all conditioning strategies when based on SET is interesting, but begs the question - what about the unexplained differences? Work by Yao et al. (2009) and Schweiker & Wagner (2015) look beyond statistics to develop approaches that consider adaptive process along with cultural and climatic considerations to better understand different comfort expectations of building occupants. Based on this dataset and our analytical procedure, two additional hypotheses present: first is the personal control construct. This notion of personal agency in creation of one's comfort inside a building was a core principle of the original adaptive model, and has been empirically validated across diverse research designs (Baker & Standeven, 1996; Brager et al., 2004). Unfortunately, Database II does not have the necessary metrics of occupant behavior and building descriptions such as adaptive opportunities, and so a direct empirical test of this hypothesis is not possible here. However, on the basis of precedent studies by others, the causal nexus between personal control and thermal adaptability seems plausible in these data from Database II. The second possible explanation is the representativeness of data used in the analysis. The psychrometric chart (Figure 7) shows the indoor climates of AC buildings in the database were controlled to relatively tight conditions. However, if the regression line for AC buildings in Figure 6 were extrapolated, we expect their neutral temperatures would follow the same relationship observed in MM and NV buildings. Clearly the occupants of AC buildings are capable of adapting to temperatures beyond the narrow range they experience, but those buildings didn't require much environmental or behavior adjustments. It is likely, therefore, that conventional adaptive comfort models fail to establish a strong statistical association with indoor neutralities in AC buildings simply because there were too few data points in the warmer or cooler ranges of indoor temperature due to the effectiveness of HVAC systems in tightly controlling the indoor environment across a diverse range of external climates. This begs the question - if indoor temperatures in AC buildings were to drift up and down in sync with seasonal cycles prevailing outdoors, with the potential for significant energy savings, would the same adaptive comfort responses be observed for the occupants of these buildings too? This will be explored later in the Discussion section of this paper.

The strong dependence of thermal neutrality on mean indoor air temperature depicted in Figure 6 suggests the driver of adaptive thermal comfort is simply *recent thermal exposure*, regardless of the engineering or architectural strategies in place. While the simplicity of a universal adaptive theory applicable across all conditioning strategies holds intellectual appeal, on the surface it might appear to counter the original empirical evidence (de Dear & Brager 1998; Brager & de Dear 1998). Yet this is easy to reconcile when all buildings, NV, MM and even AC, are viewed as potential arenas of thermal adaptation provided their occupants can avail themselves of adaptive opportunities (Baker & Standeven, 1996; Mishra & Ramgopal, 2013). The greater the adaptive opportunity on offer, the larger the adaptive comfort effect. This should of course be bounded within some reasonable range of conditions (see Li et al., 2019), but the evidence presented in this paper suggests that adaptation isn't confined to just occupants of naturally ventilated buildings. Simplistic binary classification of buildings as AC or NV obscures the reality that they are just polar opposites on a continuum of opportunity for adaptive thermal behavior by their occupants (van der Linden et al., 2006).

4.2 Nudging adaptive comfort standards

When the first generation adaptive comfort standard was published (ASHRAE 55-2004), there was insufficient empirical evidence available to sustain rational and defensible comfort guidelines for several different contexts. The applicability of the adaptive model in ASHRAE 55 was therefore restricted to naturally ventilated buildings. In this section we elaborate some of the implications of the present analysis and propose three nudges to the model's limits of applicability specified in Section 5.4 of Standard 55-2017. It is our belief that these nudges, one for each of the conditioning strategies analyzed, will extend the relevance of adaptive principles across the built environment and serve the interests of decreasing HVAC energy use and enhancing occupant comfort.

4.2.1 Naturally ventilated buildings

The emphasis of adaptive comfort theory on naturally ventilated buildings is largely because it is the context in which occupants are most connected to outdoor temperature variations, and usually where adaptive control opportunities are most readily available. The larger Database II allowed us to explore regional differences in adaptive comfort and recommend a nudge in the standards governing its use in naturally ventilated buildings. Replicating the analysis of de Dear & Brager (1998) showed that the relationship between comfort temperatures and outdoor conditions for NV buildings (Figure 4) is very similar to what was reported over twenty years ago on a smaller database. ASHRAE Standard 55-2017 Section 5.4 presents the adaptive comfort model specifically for the purpose of defining the range of "*acceptable thermal conditions in occupant-controlled and naturally conditioned spaces*", which is expressed as:

$$t_{comf} = 0.31\ \bar{t}_{pma(out)} + 17.8 \quad (°C) \qquad \text{(Eq 1)}$$

where t_{comf} is the neutral operative temperature for indoor comfort (°C) and $\bar{t}_{pma(out)}$ is the prevailing mean outdoor air temperature (°C).

The gradient term conceptually represents an index of thermal adaptability, and both ASHRAE's adaptive comfort model (0.31) as well as CEN EN15251 (0.33) suggest that indoor comfort temperatures drift about a third of a degree for each full degree shift in prevailing outdoor temperature (Carlucci et al., 2018). The corresponding gradient of 0.28 reported in Figure 4 is slightly reduced but broadly comparable with existing adaptive comfort standards. The most notable difference lies in the Y-intercept term of 19.8°C, which is two degrees warmer than the ASHRAE model (Eq 1) and one degree warmer than CEN EN15251.

The evidence presented in Figure 4 indicates that, for all intents and purposes, the original ASHRAE adaptive comfort standard for naturally ventilated buildings closely approximates occupants' adaptability to outdoor conditions, as evidenced by the similar gradient in the regression slope between the original model (Eq 1) and the reanalysis (Figure 4). However, exploring regional differences in adaptive comfort revealed a potential nudge of the intercept term of the model for naturally ventilated buildings. It stands to reason that, along with climatic drivers and physiological adaptation, there are cultural influences shaping thermal perception of building occupants around the world (Auliciems, 1981; Yao et al., 2009; Schweiker & Wagner, 2015; Luo et al., 2018). The steeper gradient for the Asian subset in Figure 5 suggests occupants of buildings located in Asia are more thermally adaptive than what we saw in the original ASHRAE adaptive comfort standard. Mean building temperatures reported in the psychrometric chart (Figure 7) indicates that most of the buildings in the upper temperature ranges were from Asia. Warmer neutral temperatures suggest there is a need for the model to reflect regional differences beyond that described by adaptation to climate alone. We strongly believe that developing fragmented country-specific models (based on smaller datasets) would dilute the usefulness of the adaptive comfort model. Instead, an optional tweaking of the intercept term is proposed to reflect the reported regional differences. To address the higher neutral temperature, we propose a maximum +1 K offset of the y-intercept term for buildings in Western countries, and a maximum +2 K offset for those across Asia. This simple nudge maintains backwards compatibility with the original model, and offers an extensible and comprehensive solution to increased calls for specific adaptive comfort models emanating from Asia (Indraganti et al., 2014; Nguyen et al., 2012; Nicol, 2004; Singh et al., 2011; Toe & Kubota, 2013; Manu et el., 2016).

4.2.2 Mixed-mode buildings

The ability of mixed-mode buildings to switch between natural ventilation and mechanical conditioning systems has led to conflicting advice on whether heat-balance models or adaptive comfort principles should inform the thermal comfort requirements of those occupants. There was insufficient evidence in the first ASHRAE database to decide how to address mixed-mode conditioning strategies in an adaptive comfort standard. As a result, Standard 55 precludes the use of the adaptive comfort model for any building with a mechanical cooling system. But given the limited climates and programs of contemporary buildings that could truly be conditioned solely by natural ventilation, this restriction represents a significant challenge to practitioners looking to design innovative, low-energy buildings (e.g. Yang et al., 2015). ASHRAE Database II contains 14,811 records of data from 22 mixed-mode buildings, offering a reasonable empirical evidence-base to reconsider this limitation and propose a nudge to the standards to permit MM buildings to use adaptive comfort models.

The slope of the regression for mixed-mode buildings in Figure 4 generally aligns more closely with the naturally ventilated counterparts and indicates a climate-responsiveness of building occupants in mixed-mode spaces, different to those in centrally conditioned buildings. Overlapping confidence intervals suggest that some of this difference may simply be from statistical uncertainty, and the SET analysis in Figure 10 shows greater convergence after normalizing indoor thermal environments. This observation reinforces the interpretation of mixed-mode buildings as naturally ventilated designs that have air conditioning capabilities on stand-by to mitigate overheating during more extreme weather and seasonal conditions. Defining the conditions which justify switching mixed-mode buildings between cooling strategies remains a fruitful area of research, and will depend on many contextual factors for each building considering this. But beyond the particulars of an individual building's characteristics, this finding suggests that the occupants of mixed-mode buildings broadly have similar expectations of their indoor thermal environment to their naturally ventilated counterparts. They are also able to utilize many of the adaptive opportunities that may not be available to occupants of air-conditioned buildings.

The proximity of the regression lines for mixed-mode and naturally ventilated strategies in Figure 4 provides compelling evidence to nudge the limits of applicability of the ASHRAE Standard 55 adaptive comfort model to permit mixed-mode buildings. Our findings are comparable to other results from field studies of occupant comfort in mixed-mode buildings in Australia (Deuble & de Dear, 2012), India (Honnekeri et al., 2014), and China (Luo et al., 2015) that found that the adaptive model more accurately describes thermal comfort of occupants in those buildings than heat-balance methods. Recent studies in Brazilian mixed-mode office buildings (Rupp et al., 2018) found occupants adapted to indoor temperature fluctuations during the use of natural ventilation, as predicted by ASHRAE's adaptive thermal comfort model. When operating under air conditioning mode, the Rupp et al. (2018) study found the same muted dependence of indoor neutral temperatures on prevailing outdoor temperatures. When considered alongside our Database II analyses, these findings support nudging the limits of applicability of ASHRAE Standard 55 to include the use of the adaptive model for mixed-mode buildings.

4.2.3 Air conditioned buildings

Although there has been some discussion around the application of adaptive comfort theory to mixed-mode buildings, it is uncommon to hear of adaptive principles guiding the design or operation of air-conditioned buildings. Yet our present analysis showing evidence of adaptation to prevailing indoor temperatures by occupants of all conditioning strategies suggests there may be scope to do so. Perhaps the most significant nudge is to encourage practitioners to explore the potential for adaptive comfort principles to inform design criteria, set-point temperatures, and operation schedules of HVAC systems. If considering the fundamental principles of the adaptive theory – we adapt to the conditions that we are exposed to – there is no reason why the control logic of HVAC systems can't be programmed to reflect seasonal drifts in temperature within an acceptable temperature range (Li et al., 2019). This is expanded on in the next section, but it is also relevant here for suggesting a potential nudge to ASHRAE Standard 55. To encourage such a shift in practice, standards bodies such as ASHRAE should relax the tight guidelines on air conditioned buildings, most of which are premised on the artificial precision of the PMV/PPD model's predictions (Humphreys & Nicol, 2002; Cheung et al., 2019).

4.3 Nudging practice

Nudging the adaptive comfort model in light of this new analysis amounts to naught unless accompanied by some nudging of building design and operational practices. The pathway between research and practice in the built environment domain, especially in relation to indoor environmental quality, has traditionally been via building codes and regulatory documents such as standards. But ultimately it's the creative application of these standards in building design and operation that will ensure such impact. Small nudges in practice can potentially have profound effects on both energy and comfort performance of buildings.

4.3.1 Applying the adaptive model to mixed-mode buildings

At first glance, the assessment of thermal comfort in a mixed-mode building requires the evaluation of three different operating regimes.

a. *Occupied hours when spaces are conditioned solely by natural ventilation.*
b. *Occupied hours when spaces are conditioned by mechanical conditioning only.*
c. *Occupied hours that fall within an hour or two of the transition from one mode of space conditioning to the other.*

There is no agreement in either the research or professional communities about how best to define thermal comfort operating conditions for mixed-mode buildings in any of these three operation regimes. There does seem to be agreement, however, that the chosen approach requires considered discussion between the design team and the building owners (and/or managers for the occupants, if different), as well as eventual occupant education about the building operation and the occupants' role in managing their own thermal environments. We recommend that design teams consider two approaches for applying the comfort criteria for mixed-mode buildings. These suggestions form our proposed nudge to practice when working with NV buildings.

Adaptive / ramped approach: During periods (or zones) when (where) the spaces are conditioned purely by natural ventilation, the adaptive comfort model should apply. If windows are then sealed and mechanical cooling is operating (changeover mixed-mode approach), a transition period would maintain conditions in the upper reaches of the adaptive comfort temperature range. If mechanical cooling has been operating for an extended period, conditions would then ramp down to the top of the conventional PMV-based comfort zone recommended for air conditioned spaces.

Adaptive / conserving approach: the adaptive comfort criteria are consistently maintained through *all* operational scenarios. Natural ventilation is used exclusively as long as conditions are maintained within the adaptive comfort limits, and mechanical cooling is used only as needed to ensure the building temperature does not exceed the adaptive comfort maximum temperature. This is most appropriate for spaces that operate primarily in naturally ventilated mode during significant periods of the year, and where the occupants are well-educated about building performance and will play an active role in managing their own thermal environment (i.e., there is sufficient adaptive opportunity so that expectations are relaxed as well). This is the most energy-conserving approach, and we believe that the present analysis supports its implementation.

4.3.1 PMV and the adaptive model in air conditioned buildings

Air-conditioned buildings are often operated at much cooler temperatures than ASHRAE's comfort prescriptions. In the US and comparable countries such as Australia, the typical design temperatures are set at around 22°C and remain fixed through all seasons (e.g. Aghniaey & Lawrence, 2018; Mendell & Mirer, 2009; Roussac & Bright, 2012). Indeed, summertime AC setpoints are actually closer to ASHRAE's winter prescription for heavier clothing and 50%

relative humidity. The US General Services Administration (GSA) Public Building Service investigated the potential for energy savings and performance gains and identified the optimal temperature for office spaces in summer up to 25.6°C. A significant proportion of its buildings were operated at temperatures well below that, leading to 61% of building users feeling too cold. Despite the adaptive comfort messaging from the American Society of Heating, Refrigerating and Air-Conditioning Engineers, comfort practice in centrally conditioned buildings remains steadfastly *maladaptive* all year-round. These practices are shaped by extant comfort standards for AC buildings which present a graphic comfort zone on a psychrometric chart (e.g. Figure 5.3.1 in ASHRAE 55-2017) based on the popular heat-balance model of comfort known as PMV-PPD (Fanger, 1970).

What is often overlooked in over-simplistic interpretations of the PMV/PPD model is that the upper temperature limit in ASHRAE Standard 55's 0.5 clo summer comfort zone stretches all the way to 27°C at 50% relative humidity with air speeds below 0.2 m/s. Even the neutral mid-point of the summer comfort zone is at about 25.5°C. This disconnect between a standard written primarily for the air conditioning industry (ASHRAE 55-2017) and common air conditioning practice remains, to date, largely unexplained. One potential hypothesis points to industry concerns about the effects of temperatures warmer than 22°C on occupant cognitive performance, based largely on Seppanen and Fisks' (2006) meta-analysis study purporting to show a single temperature optimum for performance at precisely that temperature of 22°C. Labor costs of an office building are widely acknowledged to be orders of magnitude higher than the energy savings accruing from implementation of either PMV/PPD or adaptive models for occupant comfort, therefore providing warmer and more comfortable temperatures is considered to be too costly in commercial buildings according to the adherents of the single temperature optimum "inverted U" model (Wargocki and Wyon, 2016). The science underpinning the putative optimum performance temperature of 22°C has been thoroughly debunked (e.g. Hancock 1989; Hancock and Ganey, 2003; Zhang et al. 2019) and supplanted by the "extended-U" model. The latter fits a much larger body of experimental data than Seppanen and Fisks' inverted U model (2006) and it indicates optimum cognitive performance being maintained across a temperature range broadly consistent with the adaptive thermal comfort zone. Nevertheless, the buildings sector in western countries has strenuously ignored advice to let indoor temperatures drift away from the 22^{o}C set-point, regardless of occupant discomfort, clothing insulation and seasonal trends.

The evidence presented in this paper indicates that cooling set-points in AC buildings are currently too low by *any* standard. It is difficult to recommend suitable temperatures based on the results of AC buildings presented in Figure 4 because the neutralities were derived from building occupants adapted to overcooling. But given the strong dependence of neutrality on mean indoor temperature presented in Figure 6, it is clear that comfort temperatures in air conditioned buildings could potentially be higher if indoor temperatures were to be nudged upwards at a slow enough rate to allow for adaptation. Regarding the most appropriate neutral temperature, we believe the summertime (0.5 clo) graphic comfort zone on ASHRAE 55's psychrometric chart remains the most rational choice. This would translate to set-points between 24-27°C for relative humidity of 50% and typical air conditioned occupied zone air speeds below 0.2 m/s. But how can we transition from current summertime practices (~22°C) to temperatures more closely aligned with the PMV/PPD comfort model recommendations of 24~27°C? The CoolBiz and Setsuden campaigns (Iwahashi et al., 2014) are precedents for abrupt changes to setpoint temperatures. But given the hypersensitivity of building occupants to changes in their work environments, a sudden step-change in summertime setpoints by as much as 5°C would very likely elicit complaints. Instead, incremental steps spread out over a couple of weeks designed to nudge indoor temperatures in the direction of outdoor climate could be feasible because it affords time for occupant's adaptive behavioral and perceptual mechanisms to adjust.

5. Conclusion

The recently released ASHRAE Global Thermal Comfort Database II formed the basis of an investigation of the original ASHRAE adaptive comfort standard and exploration of additional research questions. The aim of the analysis was to reappraise the scope of applicability of the adaptive comfort standard, assess potential regional differences in adaptive comfort responses, and propose nudges to adaptive comfort theory, the adaptive comfort model and standard, and building design and operational conventions. We confirmed that the model remains valid in approximating occupants' comfort response in naturally ventilated buildings using prevailing outdoor conditions. The larger and more geographically diverse database revealed that mean indoor temperatures in buildings in Asia were typically warmer than other regions, and that occupants in those buildings were better adapted to those conditions. There were sufficient mixed-mode buildings to determine that the relationship between neutral temperatures and outdoor conditions in such buildings was aligned more closely with naturally ventilated buildings than those that were air-conditioned. We also discovered clear evidence that people adapt most strongly to prevailing *indoor* temperatures irrespective of conditioning strategy (i.e., NV, MM and AC buildings).

These findings carry significant implications for both comfort standards and building practice. As our suggested nudges, we recommend that the current ASHRAE 55 Adaptive Comfort Standard remain in place, but propose an optional 1-2K offset of the intercept term for buildings located in Asia. We also believe the current findings strongly support a modification of the limits of applicability, which should permit the use of the adaptive model for mixed-mode buildings. Finally, we suggest that building operation should better recognize occupants' ability to adapt to indoor conditions by implementing adaptive comfort algorithms to define setpoint temperatures in air conditioned buildings. This could lead to improved energy performance without sacrificing occupant comfort.

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