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# Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings

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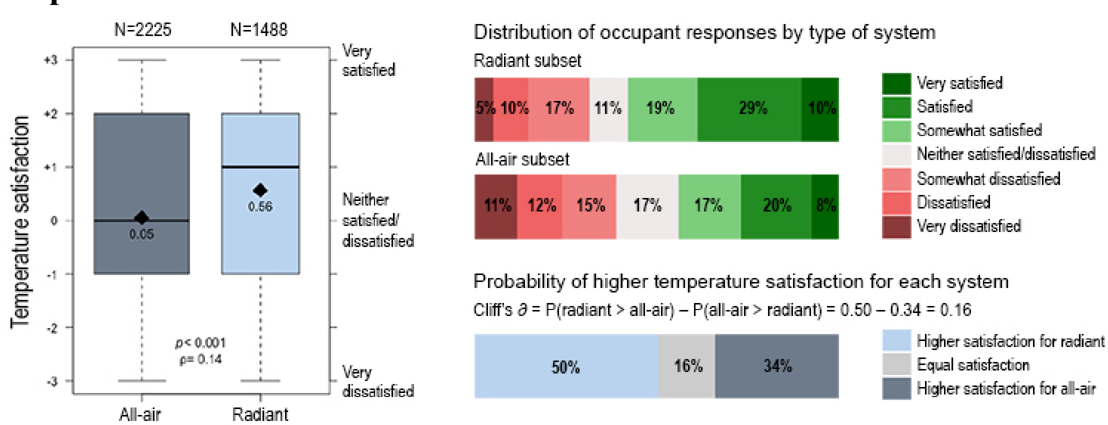
## Abstract
*There is little knowledge from occupied buildings of the impact of radiant heating and cooling systems on indoor environmental quality aspects such as thermal comfort, indoor air quality, and acoustics. We present indoor environmental quality survey results from 3,892 respondents in 60 office buildings located in North America; 34 of which used all-air systems and 26 of which used radiant systems as the primary conditioning system. In the current study, we present the survey results of 1,645 occupants in buildings with radiant systems. To our knowledge, this is the largest dataset used in a comparison of occupant satisfaction in radiant buildings. We used an existing database to extract a subset of occupant responses from all-air buildings whose key characteristics match those radiant buildings. The results indicate that radiant and all-air spaces have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings.*

## Graphical abstract




## 1 Introduction
In the U.S., people spend almost 90% of their time indoors [1]. This long exposure to indoor conditions has the potential to affect the well-being, performance and health of the occupants residing within those spaces. The design and operation of buildings also impact their energy consumption which accounts for 40% of a building's primary energy use in the U.S. [2]. With these dual challenges, researchers and building professionals seek design strategies that simultaneously provide an improved indoor environmental quality (IEQ) while reducing energy use. Radiant conditioning systems offer opportunities to achieve higher energy efficiency [3]–[7]; yet, little is known about how radiant systems affect the IEQ in buildings.

We conducted a critical literature review on thermal comfort for radiant and all-air buildings [8]. We found that multiple methods (e.g., building performance simulation, physical measurements in laboratory test chambers, physical measurements in buildings, human subject testing, occupant-based surveys) were used to compare thermal comfort between both system types [8]. The review identified eight conclusive studies: five studies that could not establish a thermal comfort preference between all-air and radiant systems [9]–[13], and three studies showing a preference for radiant systems [14]–[16]. Overall, a limited number of studies were available; and aggregating them did not help provide conclusive consensus on the effectiveness of radiant systems. The review also revealed that only a few studies were based on actual occupant perception. Aside from thermal comfort, little is known about the ways in which radiant systems affect acoustic quality in buildings. Radiant systems are installed in or on large surfaces, generally ceilings or floors. Keeping these surfaces exposed can be difficult when integrating acoustical absorbents; this can be especially challenging for thermally activated building systems (TABS). Recent laboratory studies have shown that a radiant cooled ceiling with about 45% coverage of free-hanging acoustic clouds would reduce cooling capacity by only 11% [17], [18]. Yet, in practice, concrete surfaces used in TABS are often left uncovered, which can lead to lower acoustic satisfaction [19]. Results from additional survey studies on 180 occupants (seven radiant cooled buildings including six using TABS) confirmed low acoustic satisfaction [20]. The use of radiant systems may also indirectly affect other aspects of the building design and its indoor environment. For instance, using a radiant system may affect the design of the envelope, lighting equipment, and the integration of air systems for ventilation.

The goal of this study is to compare IEQ - in particular, thermal comfort and acoustic quality – as reported by the occupants within a large set of buildings using radiant and all-air systems.

# 2 Method

## 2.1 Occupant survey method

We used the online Occupant Indoor Environmental Quality Survey administered by the Center for the Built Environment (CBE), University of California, Berkeley, to perform our data collection [21]. The survey asks a set of basic questions about occupant demographics followed by nine core categories of indoor environmental quality, including thermal comfort, air quality, acoustics, lighting, cleanliness/maintenance, spatial layout, office furnishing, and general building and workspace satisfaction. We invited occupants in each building to take the survey through an invitation e-mail that included a URL to the survey for their building. The survey measures occupant satisfaction in each of the above categories using a 7-point Likert scale with answers ranging from 'very satisfied' to 'very dissatisfied' with 'neither satisfied nor dissatisfied' as the middle option (see Figure 1). This survey is a web-based survey and, depending on the question, dissatisfied responses trigger branching questions targeting the source of that dissatisfaction. The survey takes participants approximately 10-15 minutes to complete, depending on the number of branching questions received, and open-ended comments provided.

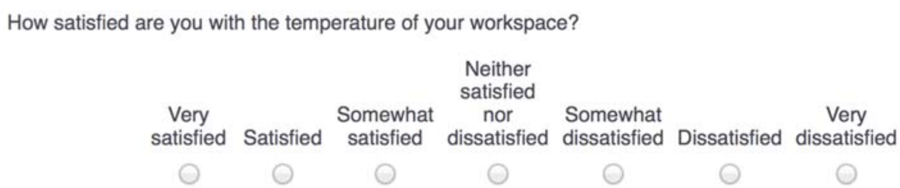



*Figure 1: Sample of survey question (satisfaction with temperature) using a 7-point Likert scale*

For each building where we administered an occupant survey, we also conducted a survey of the building's characteristics, specifically: location, size, year of construction or renovation, type of HVAC system(s), green building certification, energy use, etc. Either the building manager, the facilities manager, or a member of the design team provided this information in each case.

CBE has conducted surveys in over 1000 buildings with about 100,000 individual occupant responses since 2001, primarily in the U.S.. Building types cover commercial offices, healthcare, laboratories, educational buildings, libraries, residential, etc. This database represents a unique research resource that has been used, for instance, to assess which parameters have the largest effect on occupant satisfaction [22], to evaluate the effectiveness of office layout [23], HVAC strategies [24]–[26], or building rating systems [27], [28].

## 2.2 Selection of buildings and collection of data

While the existing CBE survey database represents quite a large sample of buildings, only a few of those buildings used radiant systems as the primary conditioning system. This disparity reaffirms all-air as being the most common conditioning system in areas where we have conducted surveys in the past. To fill this gap, the current study involved a large effort to collect new survey data in radiant buildings. This section details the building selection criteria for both radiant and all-air groups.

### *2.2.1 Collection of data from radiant buildings*

The current study focused on radiant cooling (either as a single conditioning mode or in combination with heating) for primarily office and educational buildings in the U.S. and Canada (regardless of whether they had been renovated or were new construction). Specifically, this included: regular offices, higher education and learning centers, libraries, and government buildings. There was no restriction on the ownership type; we include both private and publicly owned buildings. We included the three major types of radiant systems: embedded surface systems (ESS); thermally activated building systems (TABS); and radiant ceiling panels (RCP). We did not include other hydronic systems that are not focused on radiant heat exchange. For buildings using mixed conditioning strategies, we made sure that the workstations for the surveyed occupants were in a radiantly conditioned area. We only included buildings that had a minimum of 15 occupants and we did not survey transient occupants (such as students or library visitors) due to their lack of continuous experience with the spaces in question.

We looked at the existing CBE survey database and found 8 buildings (568 occupants) that met the criteria above, and then sought out additional candidate radiant buildings to increase the sample size. We began with a target building set for the study based on CBE's online database of radiant buildings [29] to which we added other potential building candidates from NBI's Getting to Zero (GtZ) database [30]. We identified 146 potential building candidate and tried to reach all of them. For the buildings that met our selection criteria and agreed to participate, we administered both the CBE Occupant IEQ Survey and the building characteristics survey. As an incentive, upon completion of the occupant survey, participants were entered into a raffle to win a gift card. Building managers, facilities managers, and design team members who completed the building characteristics form also received gift cards as compensation for their support of the study. We collected this additional data between November 2015 and March 2017, and discarded the oldest survey from two buildings that we surveyed twice (i.e., we discarded two surveys from the existing CBE survey database).

### *2.2.2 Data for all-air buildings*

The data from the all-air buildings came from a subset of the CBE survey database, as described above [27]. This subset consists of commercial buildings surveyed up until 2010 and whose building characteristics our team verified. We wanted our all-air subset to conform with the characteristics of the radiant buildings collected. As a first step, we established a list of key criteria for selecting the all-air buildings that matched those of the radiant dataset. This included buildings that: (1) are located in the U.S. or Canada; (2) are offices, educational or government buildings (only office spaces surveyed); (3) use active all-air mechanical cooling systems, (4) are no older than the oldest radiant building of the subset, and (5) are of comparable size (building area) to the radiant subset (range of minimum and maximum area based on the radiant building subset). We then created a subset of all-air buildings that met these criteria.

## 2.3 Statistical analysis methods

The survey records satisfaction votes on an ordinal scale. Depending on the statistical methods, we sometimes treated our data as an interval scale, which makes the implicit assumption that the intervals between votes are treated equally. This may not be the case with satisfaction data; for example, people's perception of the difference between 'neutral' and 'slightly dissatisfied' may be larger or smaller than the difference between, say, 'moderately satisfied' to 'very satisfied'. We formatted the building's characteristics using either factors or a binary structure.

We used an occupant's individual responses as the main unit of our analysis, as it has the advantage of correctly accounting for the number of people that have answered the survey. The use of individual responses also prevents one from artificially reducing the variance and, consequentially, increases accuracy. An alternative is to use one average value for each building. In a few cases, we refer to buildings, which is a more common scale in the field (e.g., building design, operation, energy use, etc.). Using responses aggregated by building does not reduce the building design process to a collection of individual characteristics and independent decisions. Therefore, the building scale can sometimes be more representative of design intent and reveal the differences between building performance. It also prevents buildings with higher numbers of occupants from bringing bias to the overall result. We report the number of occupants per building in the results throughout this paper. We used the R statistical software v. 3.3.2 [31] for all statistical analysis.

We used multiple statistical methods in our analysis. We compared both mean and median values. Median values are more relevant in the case of ordinal categorical data as they respect the inherent limitations of the scale (respondents cannot vote in-between two categories). Yet, median values often miss providing sufficient granularity of the differences in the data. The use of mean values with interval data is delicate, but appropriate and used. It can provide complementary information that can be used to further explain differences between groups. Their use is most appropriate when the sample size is large. Therefore, we commonly reported and discussed both median and mean. We tested the statistical significance of the difference between independent groups using the Wilcoxon rank-sum test, where *p-value* < 0.05 is considered statistically significant. *P-values* are sensitive to sample size and larger samples can lead to possible over-interpretation of the results. Therefore, we complement our results with effect sizes. We used boxplots as one form of graphical representation of the results. Boxplots indicate the mean, the median, and the 1$^{st}$ and 3$^{rd}$ quartiles of satisfaction votes for each group considered.

Effect size is a quantitative measure of the strength of a phenomenon, and reflects practical significance [32]. We used Spearman rank correlations ($\rho$) because of our data structure (ordinal scale) which is a rank-based measure of association that evaluates the monotonic relationship between two continuous or ordinal variables. This type of effect size describes the magnitude of shared variance between two or more variables. Spearman's $\rho$ is kept within the interval [-1, +1] with 0 indicating no association. While the calculation of $\rho$ is straightforward, the thresholds for interpretation of effect sizes (i.e., what is meaningful or not) vary by author. Cohen [33] was the first to propose thresholds. He used 0.1, 0.3 and 0.5 to define 'small', 'medium, and 'large' effects, respectively. Cohen's values have been later increased by Ferguson [34] to the more conservative thresholds of 0.2, 0.5 and 0.8, respectively, to prevent over-interpretation of effects. Both authors commonly warn about the challenge of interpretation of effect sizes, which vary from one field to another. We could not find interpretation schemes of effect sizes commonly used in our field, and thus, we present more detail on how we address effect size thresholds in this paper. We used two separate approaches for this analysis:

1. **Comparative approach using extreme scenario in our dataset**: We used the dataset of this study (60 buildings) and generated groups of best/worst buildings based on the upper and lower 3-5 buildings of the dataset (enough to include about 120 occupants on either side). We conducted this analysis for the IEQ category showing the highest effect size (which, as shown later, was temperature satisfaction). As median values tend to overlap for a wide range of buildings, we chose the best/worst buildings based on their mean values. These extreme scenarios provided a set of values against which we compared what is defined as a 'large' effect.
2. **Comparative approach using other variables in our dataset**: We used the dataset of this study and compared the effect size obtained for conditioning type (radiant/all-air) to the effect size obtained for other binary variables of our survey such as type of ventilation (mixed-mode/mechanical), type of office (enclosed/open), gender (male/female), etc. This analysis provided us with a different perspective to compare the outcome of conditioning type and it allowed us to put the discussion of effect size into context. We used several IEQ categories in this assessment.

Section 3.3.2 reports the results of our effect size analysis..

We also used Cliff's delta ($\partial$) to report effect sizes. Cliff's $\partial$ explains the probability of superiority of one variable against the other: probability that a randomly selected observation from one group is larger than a randomly selected observation from another group, minus the reverse probability (i.e., for this study, $\partial$ = P(radiant > all-air) – P(all-air < radiant)) [35]. Cliff's $\partial$ is a non-parametric test; it is not affected by the distribution of the dependent variable. Cliff's $\partial$ ranges between -1 and +1, where 0 indicates overlapping distributions. We could not find references for interpreting Cliff's $\partial$ values, but will discuss the values obtained.

Our analysis also includes linear models with mixed effects. This type of model recognizes the relationship between serial observations scaled on the same unit [36]. We used building ID and type of office as the random effect and report between-group variability.

# 3 Results and discussion

## 3.1 Description of the final dataset

We contacted a total of 141 buildings for the radiant dataset, and we obtained new data from 20 buildings (1284 occupants), which we combined with the radiant buildings from the existing CBE dataset. Our study involved 26 surveys in buildings with radiant systems and 34 in buildings with all-air systems, with 1,645 and 2,247 occupants, respectively. Table 1 summarized the source of the data used in this study. Table 1: Number of buildings and occupants surveyed available for this analysis

| | Existing CBE IEQ survey data | | Data collected | Data used for this study | |
|---|---|---|---|---|---|
| | Building from [27] | Radiant buildings | Radiant buildings | All-air buildings | Radiant buildings |
| Buildings surveyed | 144 | 6 | 20 | 34 | 26 |
| Occupants surveyed | 21,477 | 361 | 1,284 | 2,247 | 1,645 |

Table 2 summarizes the final dataset.

*Table 1: Number of buildings and occupants surveyed available for this analysis*

| | Existing CBE IEQ survey data | | Data collected | Data used for this study | |
|---|---|---|---|---|---|
| | Building from [27] | Radiant buildings | Radiant buildings | All-air buildings | Radiant buildings |
| Buildings surveyed | 144 | 6 | 20 | 34 | 26 |
| Occupants surveyed | 21,477 | 361 | 1,284 | 2,247 | 1,645 |

*Table 2: Description of the dataset used for the analysis of this paper*

| Criteria | | Radiant subset | All-air subset | Total |
|---|---|---|---|---|
| General | Occupant responses (% of total) | 1,645 (42%) | 2,247 (58%) | 3,892 (100%) |
| | Building surveys count (% of total) | 26 (43%) | 34 (57%) | 58 (100%) |
| | Occupant responses added | 1,284 (35%) | - | 1284 (35%) |
| | Building surveys added | 20 (34%) | - | 20 (34%) |
| Type of radiant system | Radiant panels | 478 (12%) | - | 478 (12%) |
| | In-slab (TABS & ESS) | 1,167 (30%) | - | 1,167 (30%) |
| | Non-radiant | - | 2247 (58%) | 1,978 (58%) |
| Ventilation systems | Mechanical ventilation (MV) | 1,038 (27%) | 1,185 (30%) | 2,036 (57%) |
| | Mixed-mode ventilation (MM) | 607 (16%) | 969 (25%) | 1,487 (40%) |
| | NA | - | 93 (2%) | 234 (2%) |
| Climates | Cold (ASHRAE zone 6A, 7) | 55 (1%) | 395 (11%) | 450 (12%) |
| | Cool (ASHRAE zone 5, 5A, 5B) | 384 (10%) | 477 (12%) | 861 (22%) |
| | Mixed (ASHRAE zone 3C, 4A, 4C) | 813 (21%) | 803 (21%) | 1,616 (42%) |
| | Warm (ASHRAE zone 3A, 3B) | 393 (10%) | 572 (16%) | 965 (25%) |
| | NA | - | - | - |
| Type of offices | Cubicles with high partitions | 157 (4%) | 336 (9%) | 493 (13%) |
| | Cubicles with low partitions | 665 (18%) | 974 (25%) | 1639 (42%) |

| | | | | |
|---|---|---|---|---|
| | Enclosed private office | 256 (7%) | 547 (14%) | 803 (21%) |
| | Enclosed shared office | 80 (2%) | 173 (4%) | 253 (7%) |
| | Open office with no partitions | 295 (8%) | 35 (1%) | 330 (8%) |
| | NA | 192 (5%) | 182 (5%) | 374 (10%) |
| Year of occupancy (construction/renovation) | 1st Quartile | 2010 | 2005 | 2006 |
| | 2nd Quartile (median) | 2012 | 2006 | 2008 |
| | 3rd Quartile | 2013 | 2008 | 2012 |
| | Max | 2015 | 2009 | 2015 |
| Building size $m^2$ | 1st Quartile ($m^2$) | 5,574 | 2,764 | 4,095 |
| | 2nd Quartile (median) | 16,020 | 6,132 | 6,763 |
| | 3rd Quartile ($m^2$) | 18,860 | 7,990 | 16,350 |
| | Max | 20,440 | 17,190 | 20,440 |

## 3.2 Occupant satisfaction in buildings using radiant systems

Figure 2 shows the distribution of the responses for each survey category. We observe that the ranking of the survey categories for occupants exposed to radiant systems follows the patterns of larger survey studies conducted (e.g. Frontzcak et al. [22]), where ease of interaction, maintenance/cleanliness, furnishing, visual comfort categories show higher results compared to temperature and acoustic questions. For the first 13 categories of this radiant systems survey (including: building cleanliness, ease of interaction, building maintenance, colors and textures, overall building satisfaction, comfort of furnishing, workspace cleanliness, workspace satisfaction, amount of light, air quality, amount of space, adjustment of furniture, visual comfort), a minimum of 79% of occupants answered neutral or satisfied with their environment on the 7-point satisfaction scale (votes ranging from "neither satisfied nor dissatisfied" up to "very satisfied" are represented in white and green tones). The focus of this paper, thermal comfort and acoustic quality, were among the four questions that received the lowest satisfaction votes: temperature, visual privacy, noise, and sound privacy. The distributions of interest are:

- temperature: 31.5% dissatisfied, 10.5% neutral and 58% satisfied
- noise: 40% dissatisfied, 14% neutral and 46% satisfied
- sound privacy: 59% dissatisfied, 14% neutral and 27% satisfied.

Aside from sound privacy, the "satisfied" votes were larger than the "neutral" or "dissatisfied" votes for each of the survey categories. The distribution of votes is not normal and is skewed towards the satisfaction range.

We looked at the source of temperature dissatisfaction (see Figure 3). The respondents rated control and access to control among the highest four sources of dissatisfaction. Occupants also referred to the air movement being too low (20% of dissatisfied answers), which is consistent with previous studies. Interestingly, the sources of dissatisfaction that many may expect in spaces using radiant systems, "hot/cold floor surfaces" and "hot/cold ceiling surfaces" were not highly reported: just 8% and 2% of dissatisfied answers, respectively.

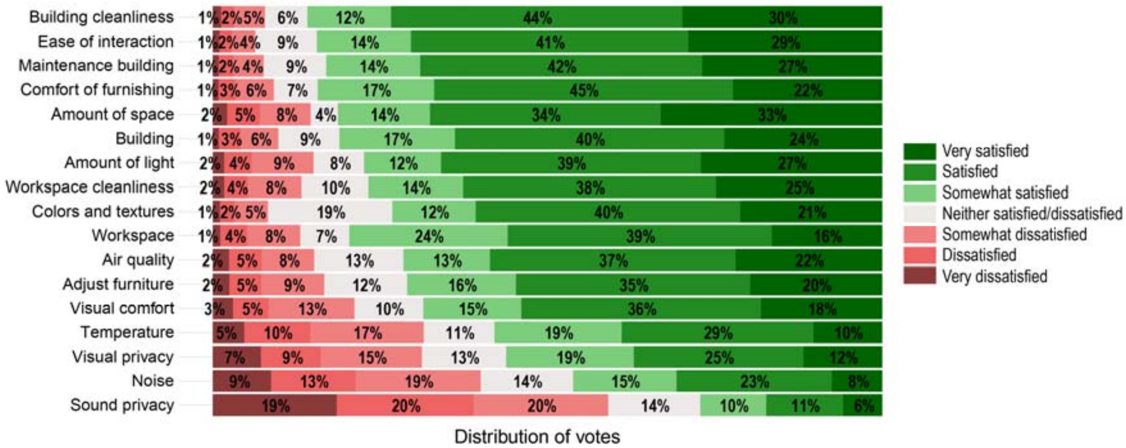



*Figure 2: Distribution of occupant satisfaction votes in buildings using radiant systems for all survey categories ordered by mean satisfaction score*

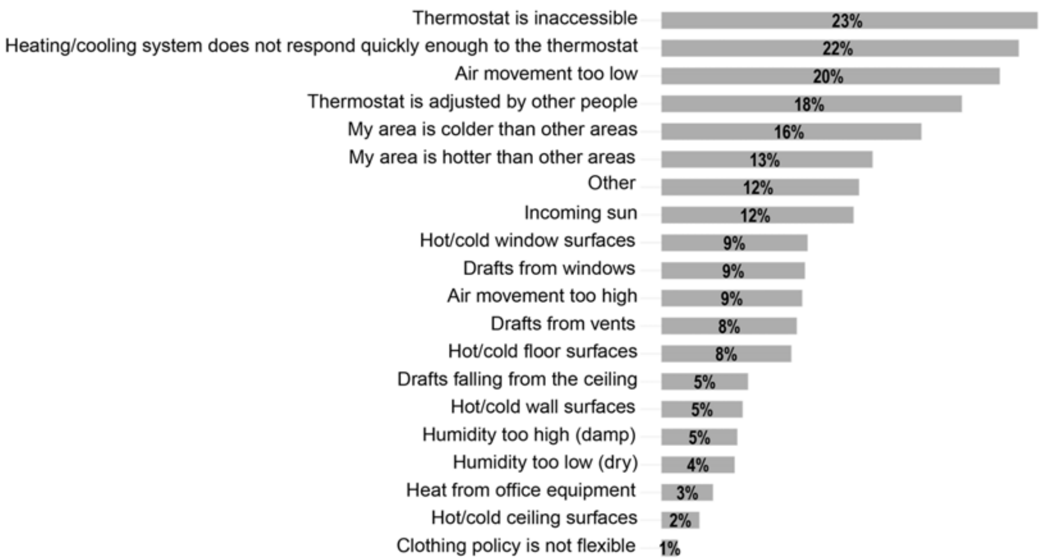



*Figure 3: Source of dissatisfaction with temperature of 611 negative votes with temperature*

## 3.3 Occupant satisfaction in radiant vs. all-air buildings

### *3.3.1 Comparison of occupant satisfaction with IEQ in radiant and all-air buildings*

Table 3 summarizes the key results of the comparison between radiant and all-air buildings. We provide the following metrics for each surveyed satisfaction question: mean, median (Mdn) and standard deviations (SD) of scores for occupants of radiant and all-air buildings; the difference in mean (ΔM) and median (ΔMdn) between the two groups; the statistical significance of the difference (*p-value*), and the effect size (Spearman's rho ($\rho$) and Cliff's delta ($\partial$)).

*Table 3: Selected results of statistical analysis between the radiant and all-air groups*

| | Radiant group | | | All-air group | | | Comparison | | | Effect size | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Satisfaction with:** [(a)] | **Mean** | **Mdn** | **SD** | **Mean** | **Mdn** | **SD** | **ΔM** | **ΔMdn** | **p-value** [(b)] | **Spearman's ρ** | **Cliff's ∂** |
| building cleanliness | 1.77 | 2 | 1.29 | 1.57 | 2 | 1.43 | 0.20 | 0 | <0.001 *** | 0.06 | 0.07 |
| ease of interaction | 1.74 | 2 | 1.26 | 1.46 | 2 | 1.46 | 0.28 | 0 | <0.001 *** | 0.09 | 0.1 |
| building maintenance | 1.67 | 2 | 1.29 | 1.38 | 2 | 1.5 | 0.29 | 0 | <0.001 *** | 0.09 | 0.1 |
| amount of light | 1.48 | 2 | 1.53 | 1.42 | 2 | 1.6 | 0.06 | 0 | 0.552 | 0.01 | 0.01 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| workspace cleanliness | 1.44 | 2 | 1.48 | 1.41 | 2 | 1.54 | 0.03 | 0 | 0.977 | 0 | 0 |
| comfort of furnishing | 1.6 | 2 | 1.28 | 1.31 | 2 | 1.53 | 0.29 | 0 | <0.001 *** | 0.08 | 0.09 |
| building | 1.54 | 2 | 1.35 | 1.28 | 2 | 1.5 | 0.26 | 0 | <0.001 *** | 0.08 | 0.09 |
| amount of space | 1.58 | 2 | 1.57 | 1.23 | 2 | 1.72 | 0.35 | 0 | <0.001 *** | 0.10 | 0.12 |
| colors and textures | 1.42 | 2 | 1.35 | 1.27 | 2 | 1.59 | 0.15 | 0 | 0.146 | 0.02 | 0.03 |
| workspace | 1.33 | 2 | 1.37 | 1.15 | 2 | 1.47 | 0.18 | 0 | 0.001 ** | 0.06 | 0.06 |
| air quality | 1.27 | 2 | 1.56 | 1.13 | 2 | 1.59 | 0.14 | 0 | 0.002 ** | 0.05 | 0.06 |
| adjustment of furniture | 1.19 | 2 | 1.56 | 1.08 | 2 | 1.65 | 0.11 | 0 | 0.095 | 0.03 | 0.03 |
| visual comfort | 1.08 | 2 | 1.63 | 1.04 | 2 | 1.69 | 0.04 | 0 | 0.732 | 0.01 | 0.01 |
| visual privacy | 0.5 | 1 | 1.78 | 0.38 | 1 | 1.96 | 0.12 | 0 | 0.19 | 0.02 | 0.03 |
| **temperature** | **0.56** | **1** | **1.71** | **0.05** | **0** | **1.82** | **0.51** | **1** | **<0.001 ***** | **0.14** | **0.16** |
| noise | 0.14 | 0 | 1.79 | 0.22 | 0 | 1.82 | -0.08 | 0 | 0.223 | -0.02 | -0.02 |
| sound privacy | -0.66 | -1 | 1.83 | -0.64 | -1 | 1.94 | -0.02 | 0 | 0.876 | 0 | 0 |

(a) We ordered the results by mean satisfaction score for each category based on the full database. We indicate in bold the variable for which there is the largest difference between the two groups; (b) ***p<0.001 highly significant; **p<0.01 significant; *p<0.05 less significant; (blank) not significant

When comparing the two types of building systems, temperature satisfaction shows the largest difference in all these measures ($\Delta$M=0.51, $p$<0.001, $\Delta$Mdn=1, ρ=0.14, ∂=0.16) in favor of the radiant subset. In Figure 4 (left), we show boxplots of temperature satisfaction for radiant and all-air systems. Although the effect size based on Spearman's $\rho$ was larger for temperature satisfaction than the other survey categories, it could be considered as either negligible ($\rho < 0.2$) or small ($0.1 \leq \rho < 0.3$) depending on the reference used for effect size thresholds [33], [34], or otherwise given the lack of established effect size thresholds for our field. In section 3.3.2, we conduct more analysis on the interpretation schemes of this index.

After temperature satisfaction, the second biggest difference in means is for satisfaction with perceived amount of space, but with no difference in median values ($\Delta$M=0.35, $p$<0.001, $\Delta$Mdn=0. ρ=0.1, ∂=0.12). Aside from temperature satisfaction and perceived amount of space, the overall differences observed between the radiant and all-air groups are very small, with no difference in median, and negligible effect size. Overall building satisfaction shows a difference in means of 0.26 ($\Delta$M=0.26, $p$<0.001, $\Delta$Mdn=0, ρ=0.08, ∂=0.09) in favor of the radiant subset. Acoustic satisfaction (noise and sound privacy) did not show statistically significant differences between the radiant and all-air groups. This is noteworthy because previous survey results had indicated lower acoustic satisfaction with radiant buildings due to large areas of exposed concrete surfaces [19]. Additional analysis by type of office is reported in section 3.3.4 to provide further insights into the acoustic satisfaction.

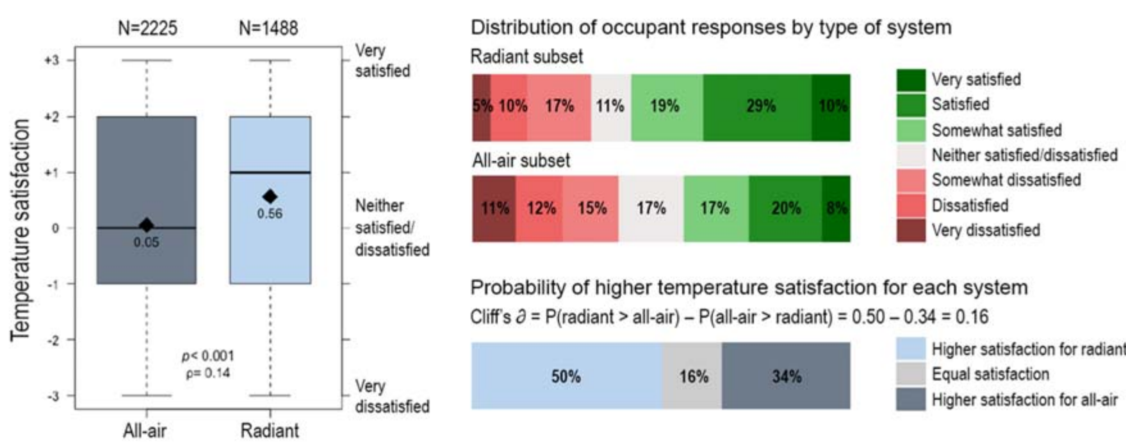


*Figure 4: (Left) Boxplot of temperature satisfaction in which diamond dots represent mean values; (upper right) Bar chart showing the distribution of temperature satisfaction; and (lower right) Probability of higher temperature satisfaction for the radiant and all-air conditioning subsets.*

### *3.3.2 Effect size analysis*

This analysis follows the methodology described in section 2.3. It focuses on two effect size metrics suitable for ordinal scales: Spearman's rho ($\rho$) and Cliff's delta ($\partial$).

**Spearman's rho ($\rho$) interpretation: comparative approach using extreme scenario in our dataset**

We used Spearman's rho ($\rho$) effect size as a measure of association. We followed the method defined in section 2.3 to generate scenarios of 'best' vs. 'worst' groups, which we compared against one another using Spearman's rho effect size. We conducted this analysis using temperature satisfaction which, as noted previously, showed the highest effect size. Table 4 reports the results of this analysis and shows a difference in means between the extreme groups of 2.82, which is substantial (47% of the scale). The effect size is $\rho$=0.65, which represents a large effect according to Cohen [33], but only a moderate effect according to Ferguson [34]. The two authors propose the values of 0.5 and 0.8, respectively, as their thresholds for large effect. The Spearman's rho obtained for our extreme scenarios is exactly in-between these two cited thresholds for a large effect. This analysis aimed to contextualize the threshold proposed. Cohen's thresholds have been criticized for over-interpretation. On the other hand, according to Ferguson's thresholds, the difference between the best 3-5 and worst 3-5 buildings in a 60 building sample (i.e. an extreme scenario) would be defined as 'moderate', not 'large', which may be unreasonable. As noted above, both Cohen and Ferguson commonly warn about the challenge of interpretation of effect sizes, which vary from one field to another, and our field does not yet have accepted values for these thresholds. Defining appropriate effect size thresholds is difficult and beyond the scope of this paper. From this comparison, we can infer that there is a tendency of higher temperature satisfaction for radiant systems, but with either a negligible or small practical significance.

*Table 4: Resulting effect sizes for extreme scenarios*

| Scenario | ∆Mean | Effect size Spearman's ρ |
|---|---|---|
| 3-5 best/worst buildings for temperature satisfaction<br>~ 106 vs. 132 votes (the two groups represent 6.1% of the full sample) | 2.82 | 0.65 |

**Spearman's rho ($\rho$) interpretation: comparative approach using other variables in our dataset**

In this section, we used the total sample of this study (from the 26 radiant and 34 all-air buildings). We re-created two groups based on a series of variables: ventilation strategy (mixed-mode vs. mechanical), building size (≥ or < median size), building age (≥ or < median age), window to wall ratio (WWR) (> or ≤ 50%), distance to window (≤ or >4.6 m), type of office (open office vs. enclosed), and gender (male or female). Table 5 compares the two groups against each other using differences in means, medians, *p-values* and Spearman's rho effect sizes. The results provide a way to compare the outcome obtained for our radiant vs. all-air analysis to other variables. We note that, for all the variables tested, gender has the highest effect size for temperature satisfaction ($\rho$=0.2), followed by conditioning type ($\rho$=0.14). The other variables show low effect size comparatively. Karjalainen [37] conducted a meta-analysis to determine the impact of gender on thermal comfort. His results showed that females were more likely than males to express thermal dissatisfaction (odds ratio: 1.74, 95% confidence interval: 1.61–1.89). He concluded that there was a statistical difference based on p-value, but did not comment on effect size thresholds for practical significance. Applying Ferguson's proposed thresholds, where an effect size less than an odds ratio of 2 is a "negligible" effect, would suggest that the effect of gender within Karjalainen's analysis remains below the recommended minimum effect size for a practically significant effect. For our sample, gender just reaches the threshold of 'small' practical significance according the Ferguson's scale for Spearman's rho. The value of Spearman's rho corresponding to type of conditioning (radiant vs. all-air) was lower than the Spearman's rho corresponding to gender. Therefore, as with gender, we can conclude that there is a tendency toward higher temperature satisfaction for radiant systems, but with either a negligible or small practical significance.

*Table 5: Comparison of effect size for building characteristics*

| Category | Variables | Group 1 | Group 2 | Comparison | | | Effect size |
|---|---|---|---|---|---|---|---|
| | | | | ∆Mean | ∆Mdn | p-value | Spearman's ρ |
| temperature satisfaction | gender | male | female | 0.74 | 1 | <0.001 *** | 0.2 |
| | conditioning | radiant | all-air | 0.51 | 1 | <0.001 *** | 0.14 |
| | ventilation strategy | mixed-mode | mechanical | 0.09 | 1 | 0.139 | 0.02 |
| | building size | < median (6763 $m^2$) | ≥ median (6763 $m^2$) | -0.07 | -1 | 0.241 | -0.02 |
| | WWR | ≤ 50% | > 50% | 0.09 | 0 | 0.221 | 0.02 |
| | distance to window | close (≤4.6 m) | far away (>4.6 m) | 0.05 | 1 | 0.535 | 0.01 |
| | type of office | enclosed office | open office | -0.02 | 0 | 0.898 | 0 |

**Cliff's delta (∂): probability of higher, lower and equal temperature satisfaction**

We looked at the Cliff's delta (∂) effect size that, in our case, measures the probability of higher temperature satisfaction. We also decomposed the Cliff's delta equation to determine the probability that a randomly selected observation from the radiant group has higher satisfaction than a randomly selected observation from the all-air group P(radiant > all-air), its reverse probability P(all-air < radiant), and the probability of equal satisfaction P(radiant = all-air). In a space using a radiant system, a person has a 50% chance of having a higher temperature satisfaction rating, a 16% chance of having an equivalent rating, and a 34% chance of having a lower temperature satisfaction rating than in an all-air building. Figure 4 (lower right) displays the distribution of these three probabilities. The Cliff's delta associated with this analysis is ∂=0.16 (or 50%-34%=16% probability of higher temperature satisfaction for occupants in buildings with radiant systems). We could not find references for interpretation for Cliff's delta values. Thus, this analysis should be viewed as a useful means of interpreting the results of the survey, and nothing more.

*3.3.3 Analysis by building*

In this section, we move from individual responses to building scores as the main unit of analysis. Figure 5 shows the distribution of temperature satisfaction for each building ordered by means. We represent each building equally, independently from the number of votes. Buildings with radiant conditioning systems dominate the upper third of the graph; they demonstrate higher means and medians than all-air buildings.

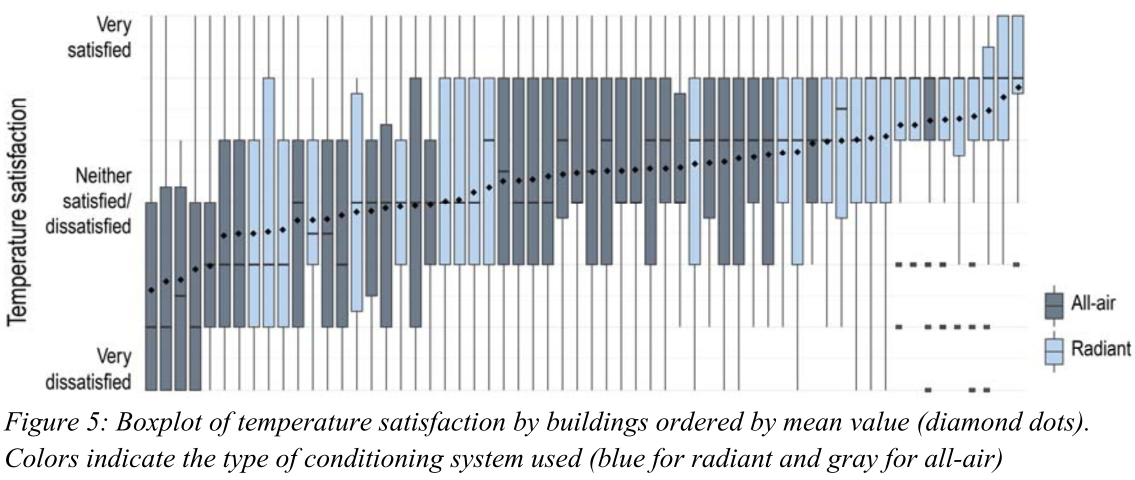



*Figure 5: Boxplot of temperature satisfaction by buildings ordered by mean value (diamond dots). Colors indicate the type of conditioning system used (blue for radiant and gray for all-air)*

**ASHRAE Standard 55's objective of 80% satisfied occupants**

Per ASHRAE Standard 55-2013 [38] with approved addenda and errata as of 2016, buildings are intended to achieve 80% satisfaction with regards to thermal comfort. The standard defines a method of assessment based on occupant survey results: "the probability of occupants satisfied shall be predicted from seven-point satisfaction survey scores by dividing the number of votes falling between -1 and +3 inclusive, by the total number of votes". We assessed this objective with the buildings of our study based on temperature satisfaction for both the radiant and all-air subsets. We also assessed ASHRAE's 80% objective by looking at 'neutral to satisfied' and 'slightly satisfied to satisfied' votes, as the latter is what was prescribed in the original version of the standard [39]. Table 6 and Figure 6 reports the results. This analysis shows that 57% of the buildings of this study meet the requirements of the current standard (slightly better results for the all-air group). Reducing ASHRAE's requirement to the 'neutral to satisfied' votes brings a significant drop. Only 10% of the buildings would comply with this definition of satisfied. When accounting only for positive votes ('slightly satisfied' to 'very satisfied' rating), as in the original version of the standard, only 2 radiant buildings (out of 26) and none of the all-air buildings of this study provided a satisfactory thermal comfort level to at least 80% of their occupants. If we look more closely at the larger database from [27] (144 buildings), 44% of the buildings meet the 'slightly dissatisfied' to 'very satisfied' interval, 10% meet the 'neutral' to 'very satisfied' interval, and only 1% meet the 'slightly satisfied' to 'very satisfied' interval. In other words, the buildings of this study are outperforming the larger sample. We note that this study did not comply with the response rate suggested by the standard (section 7.3.1 [39]) for all the buildings in the analysis. Despite this point, we may not expect a large difference in the outcome. This analysis showed that this standard's objective for thermal comfort assessment based on occupant satisfaction surveys does not appear realistic in its practical application. The number of complying buildings remains surprisingly low, despite the fact that the current proposed metric includes 'slightly dissatisfied' votes among positive responses. This inclusion is further questionable as it brings a contradiction to the definition of thermal comfort according to the same standard ("the condition of mind that expresses satisfaction with the thermal environment").

*Table 6: Percent of buildings that provide 80% occupant satisfaction with temperature*

| | % of building that shows a **slightly dissatisfied to very satisfied rating** (-1 to +3 votes) for at least *80%* of its occupants[(a)] | % of building that shows a **neutral to very satisfied rating** (0 to +3 votes) for at least *80%* of its occupants | % of building that shows a **slightly satisfied to very satisfied rating** (+1 to +3 votes) for at least *80%* of its occupants[(b)] |
|---|---|---|---|
| Radiant | 54% (14/26 buildings) | 15% (4/26 buildings) | 8% (2/26 buildings) |
| All-air | 59% (20/34 buildings) | 6% (2/34 buildings) | 0% (0/34 buildings) |
| Radiant & all-air | 57% (34/60 buildings) | 10% (6/60 buildings) | 3% (2/60 buildings) |
| Database [27] | 44% (63/144 buildings) | 10% (14/144 buildings) | 1% (2/144 buildings) |

[(a)] As in ASHRAE Standard 55-2013 (2016 update), section 7.4.1 [38];

[(b)] As in ASHRAE Standard 55-2013 (original version), section 7.4.1 [39]

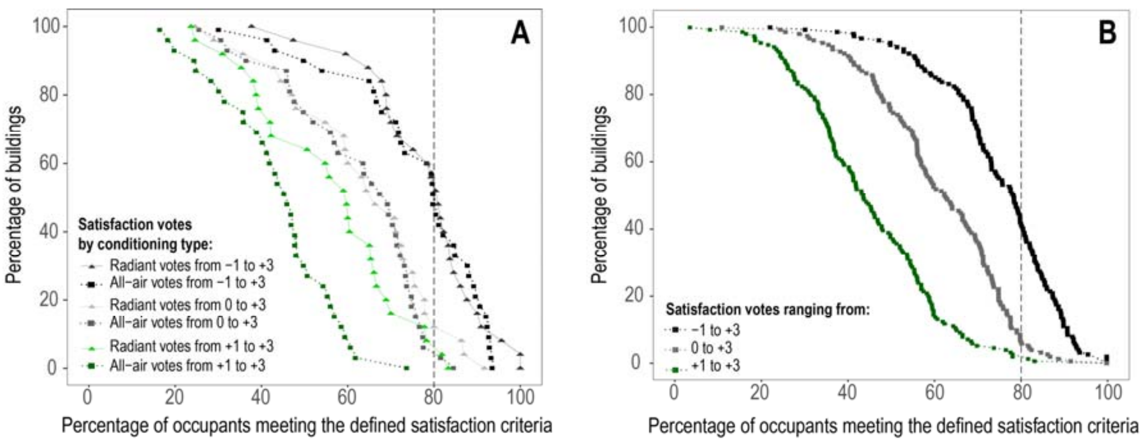



*Figure 6: Percentage of building meeting the ASHRAE Standard 55-2013 objective of 80% satisfied occupants for (A) the radiant and all-air buildings of this study, and (B) the 144 buildings from [27]. The 80% satisfaction objective is represented with a vertical dashed line.*

*3.3.4 Mixed-effects models for temperature and acoustic satisfaction*

**Mixed-effects models for temperature satisfaction**

Table 7 presents the results of testing a mixed-effect linear model to predict temperature satisfaction based on radiant and all-air conditioning types. We used 'building' as a random effect. We calculated the random effect (between groups variability) based on the intercept and residual standard deviations. The random effect reached 12%, which means that 'between-building' differences describes 12% of the overall variance in temperature satisfaction (as Figure 5 suggests). The regression coefficient, in this case corresponding to the difference in means for temperature satisfaction between radiant and all-air subsets, equals 0.52 with random effect. In section 3.3.1, this difference reached 0.56 without random effect. This outcome suggests a minor impact of the random effect of 'building' on temperature satisfaction.

*Previous studies have emphasized the impact of type of ventilation (mechanical vs. mixed-mode ventilation) on occupant temperature satisfaction [25]. We used a mixed-effect linear model with interactions to predict the combined effect of conditioning types (radiant/all-air) and ventilation types. For this model, the fixed intercept describes the prediction of temperature with all-air and mechanical ventilation. The three regression coefficients to temperature satisfaction are associated with: 'radiant', 'mixed-mode ventilation', and for the interaction of 'radiant and mixed-mode ventilation'. Only the correlation for 'radiant' is statistically significant. Its regression coefficient (0.59) is higher than in the previously tested models, but does not account for the ventilation strategy (as it is not a statistically significant outcome). This analysis reveals that the type of ventilation cannot explain further differences in temperature satisfaction, thus we exclude this variable in subsequent models. We used a mixed-effect linear model to determine the correlation between conditioning types (radiant/all-air) and climates on temperature satisfaction (see Table 1: Number of buildings and occupants surveyed available for this analysis*

| | Existing CBE IEQ survey data | | Data collected | Data used for this study | |
|---|---|---|---|---|---|
| | Building from [27] | Radiant buildings | Radiant buildings | All-air buildings | Radiant buildings |
| Buildings surveyed | 144 | 6 | 20 | 34 | 26 |
| Occupants surveyed | 21,477 | 361 | 1,284 | 2,247 | 1,645 |

Table 2 for the detail of types of climates). Only the regression coefficient for 'radiant' reached statistical significance (regression coefficient of 0.51, p=0.01). The difference between climates cannot explain the differences observed in temperature satisfaction, thus we also excluded this variable in subsequent models.

*Table 7: Linear models -with and without mixed-effects- for temperature and acoustics categories*

| Prediction of | Variables | Population | Equation for random effect | Intercept (fixed) | Regression coefficient | Random effect | Difference rad / all-air |
|---|---|---|---|---|---|---|---|
| temperature | conditioning | Full sample | 1 \| bldg. ID | 0.10 [(a)] | 0.52 (p=0.005) cond. -Radiant | 12% | +0.52 (radiant) |
| temperature | conditioning * ventil. type | Full sample | 1 \| bldg. ID | 0.03 [(b)] | 0.59 (p=0.03) cond. -Radiant<br>0.26 (p=0.28) ventil. type -MM<br>-0.26 (p=0.48) interact. | 12% | +0.59 |
| temperature | conditioning + climate | Full sample | 1 \| bldg. ID | -0.29 [(c)] | 0.51 (p=0.006) cond. -Radiant<br>0.40 (p=0.24) climate-Cool<br>0.48 (p=0.15) climate-Mixed<br>0.41 (p=0.25) climate-Warm | 12% | +0.50 (radiant) |
| noise | conditioning (radiant by type) | Full sample | 1 \| office type | 0.23 [(a)] | 0.02 (p=0.78) cond. -Inslab<br>0.03 (p=0.72) cond. -Panels | 8% | n.s. |
| sound privacy | conditioning (radiant by type) | Full sample | 1 \| office type | -0.61 [(a)] | 0.17 (p=0.02) cond. -Inslab<br>0.05 (p=0.58) cond. -Panels | 21% | n.s. |

[(a)] intercept for all-air; [(b)] intercept for all-air and mechanical ventilation; [(c)] intercept for all-air and 'very cold' climate

**Mixed-effects models for acoustic satisfaction**

Buildings using radiant systems are often associated with lower acoustical quality; this is particularly the case for ESS and TABS types of radiant systems due to large, exposed, and acoustically reflective surfaces [19]. Based on Table 3, neither of the two acoustic categories (noise and sound privacy) showed statistically significant differences in satisfaction ratings between the radiant and all-air subsets. Previous occupant satisfaction studies have shown that the type of office has a major impact on acoustic satisfaction [22], [23]. We used a mixed-effect model with 'type of office' as random effect in order to understand how much this variable can explain the variance for acoustic satisfaction. Our dataset comprised five 'type of office': cubicles with high partitions, cubicles with low partitions, enclosed private office, enclosed shared office, open office with no partitions. For this model, we also distinguished in-slab (ESS & TABS) from panel (RCP) types of radiant systems. Table 7 presents the results of these models. The output for noise satisfaction was not statistically significant between the two groups. Satisfaction with sound privacy showed a weakly significant regression coefficient (+0.17, $p$=0.02) in favor of in-slab radiant systems compared to all-air systems. The random effect equaled 21% suggesting that the large spread in the variance can be described by 'between office type' differences. In Figure 7, we can clearly see that sound privacy is more of an issue for open space offices (with or without partitions). Overall these results reveal that acoustic satisfaction categories are comparable across the two conditioning types. This outcome is relevant because it provides evidence disproving common biases against radiant systems specifically. Acoustic satisfaction appears as most challenging aspect in regard to occupant satisfaction in buildings.

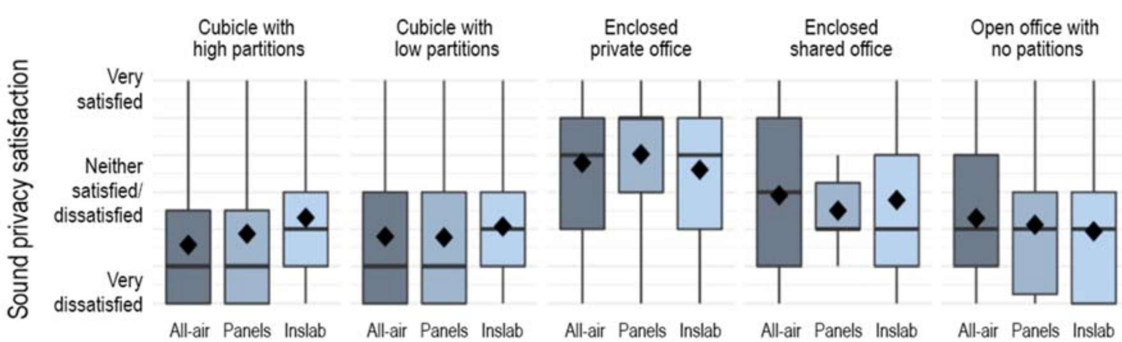


*Figure 7: Boxplots of sound privacy satisfaction for different types of conditioning systems (all-air, radiant panels and radiant inslab) and in different types of offices. Diamond dots represent mean values*

## 3.4 Study limitations

We selected the buildings of this study following the methodology detailed in section 2.2. Collecting data for the radiant subset was difficult due to the general lack of buildings with radiant conditioning in North America. As described above, we sampled the all-air buildings data from a larger database based on characteristics that followed the radiant buildings demographical and physical characteristics (see section 2.2.2). Overall, the buildings of this study (both conditioning types) have a higher environmental quality compared to the average building of the CBE survey database. As a reference, the mean overall workspace and overall building satisfaction ratings considering the entire CBE database are 0.93 (N=76,598) and 1.06 (N=80,869), respectively, while they reach 1.22 (N=3,573) and 1.38 (N=3,574), respectively, for all the buildings of this study. This study involved 26 radiant surveys and 34 all-air buildings, with 1,645 and 2,247, occupants respectively. While this is a large sample size, it is not a randomized statistically-representative sample, which is a limitation of the study.

*We sampled the all-air buildings by creating a subset of the CBE IEQ survey database from 2011 [27]. The radiant subset was mostly based on survey data collected within the framework of this study (2016 and 2017). This difference in database collection times resulted in a difference in age of buildings between the two subsets (a difference in median year of construction of 6 years, see Table 1: Number of buildings and occupants surveyed available for this analysis*

| | Existing CBE IEQ survey data | | Data collected | Data used for this study | |
|---|---|---|---|---|---|
| | Building from [27] | Radiant buildings | Radiant buildings | All-air buildings | Radiant buildings |
| Buildings surveyed | 144 | 6 | 20 | 34 | 26 |
| Occupants surveyed | 21,477 | 361 | 1,284 | 2,247 | 1,645 |

Table 2 for more detail). Frontzcak et al. [22] qualitatively observed that building age affects building satisfaction, though the categories of building age differed by decades instead of years. In the context of the length of the lifetime of a typical building, and the pace of change in the industry regarding common design practice and material selection, we do not believe this age difference is a major confounding factor, but this unavoidable disparity between the two datasets may have had an effect of the overall study results.

While temperature satisfaction showed the largest difference between the radiant and all-air subsets, there was also a difference in means for overall building satisfaction between the two groups ($\Delta$M=0.26, $p$<0.001, $\Delta$Mdn=0. $\rho$=0.08, $\partial$=0.09). Though statistically significant, this has negligible practical significance based on the effect size thresholds discussed earlier. However, this difference might indicate that buildings with radiant systems offer a slightly more satisfactory building design, an interpretation that we believe may be realistic. We performed this study on buildings in the U.S. and Canada, where radiant systems are not common practice. Designers adopting radiant systems in these locations go beyond ‘business as usual’, which brings with it a certain ambition and motivation and may trigger a more thoughtful design process. This in turn, may be reflected in the overall results.

The satisfaction questions within the CBE survey are based on an ordinal scale. In the present analysis, we often treated these observations as though they were on an interval scale, which assumes an equal distance between answers (e.g., same interval between ‘slightly satisfied’, ‘satisfied’, ‘very satisfied’). This is a common simplification in this field as interval scales allow for analysis using descriptive statistics and modelling (analysis of means and linear models). Other types of analysis (rank based correlations, analysis of medians, probability of superiority, Spearman rho effect size) respected the ordinal structure of the data.

Our paper included an analysis on effect size interpretation thresholds as a precedent for discussion as we could not find thresholds that are representative of our field in existing publications. Further research in this area may yield a different overall conclusion as to the practical significance of the observed and reported effect sizes.

# 4 Conclusions

We used the CBE IEQ occupant survey to compare occupant satisfaction with their indoor environment in radiant and all-air conditioned buildings. This study involved the administration of new occupant satisfaction surveys to 1,284 people (20 buildings) exposed to radiant systems. We supplemented this dataset with responses from 361 occupants (6 buildings) previously collected. For the all-air sample, we used a subset of the CBE database that aligned with key building characteristics of the radiant subset. This comparison involved 1,779 respondents from 26 buildings with radiant systems and 1,978 respondents from 34 buildings with all-air systems. To our knowledge, this is the largest such dataset used in a comparison study of occupant satisfaction in radiant buildings. The main conclusions of this study are:

- The analysis shows that radiant and all-air buildings have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings.
- From this dataset, a person has a 50% chance of experiencing a higher temperature satisfaction in a space using a radiant system compared to an all-air system. The reverse probability reaches 34%. There is a 16% chance for the two systems to bring equal satisfaction.
- Acoustic satisfaction showed the lowest scores from all the categories surveyed. This result shows acoustical quality to be the most challenging aspect in regard to occupant satisfaction in buildings. It is important for designers to pay more attention to improve acoustical experience in buildings. We observed equal acoustic satisfaction (noise and sound privacy) in radiant and all-air systems, disproving some commonly held biases against radiant systems.
- Less than 60% of the buildings used in this analysis met the ASHRAE Standard 55 thermal comfort objective based on post-occupancy surveys. This result is surprisingly low, in particular as the current metric within the standard includes ‘slightly dissatisfied’ votes among the positive comfort responses. This observation raises questions regarding the practicality and applicability of the comfort metric as currently written.

# 5 Acknowledgment

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