# Occupant Satisfaction in 60 Radiant and All-air Building:
## Comparing Thermal Comfort and Acoustic Quality

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*ABSTRACT: Radiant heating and cooling systems have the potential to save energy and are widely used in zero net energy buildings. Their positive and negative impacts on indoor environmental quality and, in particular, thermal comfort compared to all-air systems are still debated in the literature. This paper presents indoor environmental quality survey results from 3,892 respondents in 60 office buildings located in North America. 34 (2,247 respondents) of these buildings utilized all-air systems and 26 (1,645 respondents) utilized radiant systems as primary conditioning system. Our results indicate that radiant and all-air buildings have equal indoor environmental quality, including acoustic performance, with a tendency towards improved temperature satisfaction in radiant buildings.*
*KEYWORDS: Occupant satisfaction, Indoor Environmental Quality, Radiant systems, Post-occupancy evaluation, Thermal comfort*

### 1. INTRODUCTION

U.S. adults are estimated to spend nearly 87% of their lives indoors (Klepeis et al. 2001). This long exposure to indoor conditions has the potential to affect the well-being, performance and health of the occupants residing within those spaces. Design and operation of these spaces also impacts building energy use, which accounts for 40% of U.S. primary energy use (US DOE 2011). With these dual challenges, researchers and building professionals seek design strategies to simultaneously address both indoor environmental quality (IEQ) and energy use.

Building designers motivated to include radiant heating and cooling systems for energy efficiency considerations (Babiak et al. 2009; Feustel et al. 1995; Thornton et al. 2009; Thornton et al. 2010; Leach et al. 2010) are often concerned about how these systems might impact various aspects of indoor environmental quality, such as thermal comfort, indoor air quality, and acoustics. We completed a critical literature review to learn if spaces using radiant system provide a better, lower or equal thermal comfort compared to those spaces using an all-air system (Karmann et al. 2017). Among the eight conclusive studies we identified, five could not establish a thermal comfort preference between all-air and radiant systems, and three studies showed a preference for radiant systems. Considering the limited number of studies available, we could not establish a definitive statement on the effectiveness of radiant systems for thermal comfort. The same review revealed a lack of studies based on occupant's perception. Aside from thermal comfort, little is known about the ways in which radiant systems affect space acoustics. Radiant systems are commonly installed on large surfaces (e.g., ceilings or floors) that are kept uncovered to allow thermal radiation. In practice, exposed concrete surfaces used for massive in-slab systems can lead to lower acoustic satisfaction (Bauman et al. 2012). The use of radiant systems may also indirectly affect other aspects of a building's design, such as its envelope or the integration with air systems that provides ventilation.

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

### 2. METHODS

#### 2.1 Occupant IEQ Survey database

The Center for the Built Environment (CBE) at the University of California Berkeley has developed a web-based survey in order to assess occupant satisfaction with IEQ (Zagreus et al. 2004). The current database provides an opportunity to investigate what building features correlate with higher satisfaction in the workplace from an occupant's perspective. The survey asks a set of basic questions about occupant demographics followed by a series of questions addressing nine indoor environmental quality core categories including thermal comfort, air quality, acoustics, lighting, cleanliness/maintenance, spatial layout, office furnishing, and general building and workspace satisfaction. The survey uses a 7-point Likert scale to evaluate occupant satisfaction with answers ranging from 'very satisfied' (+3) to 'very dissatisfied' (-3), with a 'neutral/ neither satisfied nor dissatisfied' midpoint (0). The database currently includes over 1,000 buildings (e.g., commercial buildings, healthcare facilities, laboratories, educational buildings, libraries, etc.) and 100,000 individual occupant responses obtained over a period of more than fifteen years, mainly in North America. These buildings involve all types of conditioning systems, including traditional all-air and radiant systems.

### 2.2 Selection of buildings

For this study, we considered the following three types of systems 'radiant systems': embedded surface systems (ESS), thermally activated building systems (TABS), and radiant ceiling panels (RCP). As of March 2017, the CBE Occupant IEQ Survey database included 26 surveys completed in radiant buildings that presented the following characteristics: (1) use radiant systems as a primary conditioning type, (2) involve active radiant cooling (only or in addition to radiant heating), (3) are located in the U.S. and Canada, and (4) involve a minimum of 15 non-transient occupants working within a regular 'office' environment (e.g., building type includes offices, higher education, learning centres, libraries, and government buildings). For buildings using mixed conditioning strategies, we made sure that the workstations for the surveyed occupants were in a radiantly conditioned area. We considered both new and renovated construction.

The all-air building data came from a subset of the CBE survey database consisting of commercial buildings surveyed up until 2010 and whose building characteristics we verified (Altomonte et al. 2013). We wanted our all-air subset to conform with the characteristics of the radiant buildings collected. This included buildings that use active all-air mechanical cooling systems, were of similar types and locations as the radiant subset, were no older than the oldest radiant building of the subset, and were of comparable size (building area) to the radiant subset (range of minimum and maximum area based on the radiant building subset).

### 2.3 Description of the dataset

The dataset used for this study is detailed in Table 2. Our study involved 26 radiant surveys and 34 all-air buildings, with 1,645 and 2,247 occupant responses, respectively.

*Table 1: Survey count (occupants and buildings) for the dataset used for the analysis of this paper*

| | Radiant subset | All-air subset | Total |
|---|---|---|---|
| Survey count | | | |
| Occupant responses | 1,645 | 2,247 | 3,892 |
| (% of total) | (42%) | (58%) | (100%) |
| Buildings count | 26 | 34 | 58 |
| (% of total) | (43%) | (57%) | (100%) |

*Table 2: Detailed description of the radiant and all-air subset*

| | Radiant subset | All-air subset | Total |
|---|---|---|---|
| Radiant type | | | |
| 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 6A, 7) | 55 (1%) | 395 (11%) | 450 (12%) |
| Cool (ASHRAE 5, 5A, 5B) | 384 (10%) | 477 (12%) | 861 (22%) |
| Mixed (ASHRAE 3C,4A,4C) | 813 (21%) | 803 (21%) | 1,616 (42%) |
| Warm (ASHRAE 3A, 3B) | 393 (10%) | 572 (16%) | 965 (25%) |
| NA | - | - | - |
| Type of offices | | | |
| Cubicles w/ high partitions | 157 (4%) | 336 (9%) | 493 (13%) |
| Cubicles w/ 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 w/ no partitions | 295 (8%) | 35 (1%) | 330 (8%) |
| NA | 192 (5%) | 182 (5%) | 374 (10%) |
| Year of occupancy | | | |
| 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 | 5,574 | 2,764 | 4,095 |
| 2nd Quartile (median) | 16,020 | 6,132 | 6,763 |
| 3rd Quartile | 18,860 | 7,990 | 16,350 |
| Max | 20,440 | 17,190 | 20,440 |

### 2.4 Statistical analysis methods

We used occupants' individual responses as the main unit of our analysis. The use of individual responses has the advantage of correctly accounting for the number of people that have answered the survey and it prevents one from artificially reducing the variance. We used R v.3.3.2 (R Development Core Team 2017) for all statistical analysis.

We compared both mean and median values. We tested the statistical significance of the difference between independent groups using the Wilcox rank 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 that reflect practical significance (Kraemer et al. 2003). Effect size is a quantitative measure of the strength of a phenomenon (in our case the strength of a relationship between conditioning type and satisfaction). Because of the ordinal structure of our data, we used the two following effect size metrics:

(1) Spearman's ρ that describes the correlation between variables. It is by itself a measure of effect size. Spearman's ρ is kept within the interval [-1, +1] with 1 (and -1) indicating a perfect positive (and negative) association, and a 0 indicating no association.

(2) Cliff's ∂ that explains the probability of superiority of one variable against the other (i.e., for this study, ∂ = P(radiant > all-air) – P(all-air < radiant)) (Cliff 1996). Cliff's ∂ is a non-parametric test; it is not affected by the distribution of the dependent variable. Cliff's ∂ is kept within the interval [-1, +1] with 0 indicating equal distributions.

Finally, our statistical analysis includes linear models with mixed effects to determine the correlation between conditioning type and acoustic satisfaction. Mixed effects recognize the relationship between serial observations scaled on the same unit. We used 'type of office' as the random effect and report between-group variability for acoustic satisfaction.

## 3. RESULTS

### 3.1 IEQ satisfaction in radiant and all-air buildings

Table 3 and Table 4 show the results of the comparison between radiant and all-air buildings. All IEQ satisfaction categories are reported. For each question, we provide: the mean, the 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 sizes Spearman's ρ and Cliff's ∂.

The largest difference across all measures was found for temperature satisfaction in favour of the radiant subset (ΔM=0.51, p<0.001, ΔMdn=1, ρ=0.14, ∂=0.16). Although the Spearman's ρ effect size was larger for temperature satisfaction than the other survey categories, it could be considered as either negligible or small depending on the reference used (Cohen 1988; Ferguson 2009). We further develop this analysis in section 3.2. The second largest difference in means was found for satisfaction with perceived amount of space, but with no difference in median values (ΔM=0.35, p<0.001, ΔMdn=0. ρ=0.1, ∂=0.12). Aside from these two categories, the differences observed between the radiant and all-air groups are very small, with no difference in median, and negligible effect size. Acoustic satisfaction (noise and sound privacy) did not show statistically significant and practically relevant differences between the two groups.

*Table 3: Results of statistical analysis for the radiant and all-air groups*

| Satisfaction with:[a] | Radiant group | | | All-air group | | |
|---|---|---|---|---|---|---|
| | M | Mdn | SD | M | Mdn | SD |
| building cleanliness | 1.77 | 2 | 1.29 | 1.57 | 2 | 1.43 |
| ease of interaction | 1.74 | 2 | 1.26 | 1.46 | 2 | 1.46 |
| building maintenance | 1.67 | 2 | 1.29 | 1.38 | 2 | 1.5 |
| amount of light | 1.48 | 2 | 1.53 | 1.42 | 2 | 1.6 |
| workspace cleanliness | 1.44 | 2 | 1.48 | 1.41 | 2 | 1.54 |
| comfort of furnishing | 1.6 | 2 | 1.28 | 1.31 | 2 | 1.53 |
| building | 1.54 | 2 | 1.35 | 1.28 | 2 | 1.5 |
| amount of space | 1.58 | 2 | 1.57 | 1.23 | 2 | 1.72 |
| colours and textures | 1.42 | 2 | 1.35 | 1.27 | 2 | 1.59 |
| workspace | 1.33 | 2 | 1.37 | 1.15 | 2 | 1.47 |
| air quality | 1.27 | 2 | 1.56 | 1.13 | 2 | 1.59 |
| adjust. of furniture | 1.19 | 2 | 1.56 | 1.08 | 2 | 1.65 |
| visual comfort | 1.08 | 2 | 1.63 | 1.04 | 2 | 1.69 |
| visual privacy | 0.5 | 1 | 1.78 | 0.38 | 1 | 1.96 |
| **temperature** | **0.56** | **1** | **1.71** | **0.05** | **0** | **1.82** |
| noise | 0.14 | 0 | 1.79 | 0.22 | 0 | 1.82 |
| sound privacy | -0.66 | -1 | 1.83 | -0.64 | -1 | 1.94 |

[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

*Table 4: Results of statistical analysis between the radiant and all-air groups (comparison)*

| Satisfaction with: | Comparison[a] | | | |
|---|---|---|---|---|
| | ΔM | ΔMdn | p-value | Effect size (ρ) |
| building cleanliness | 0.20 | 0 | <0.001*** | 0.06 |
| ease of interaction | 0.28 | 0 | <0.001*** | 0.09 |
| building maintenance | 0.29 | 0 | <0.001*** | 0.09 |
| amount of light | 0.06 | 0 | 0.552 | 0.01 |
| workspace cleanliness | 0.03 | 0 | 0.977 | 0 |
| comfort of furnishing | 0.29 | 0 | <0.001*** | 0.08 |
| building | 0.26 | 0 | <0.001*** | 0.08 |
| amount of space | 0.35 | 0 | <0.001*** | 0.10 |
| colours and textures | 0.15 | 0 | 0.146 | 0.02 |
| workspace | 0.18 | 0 | 0.001 ** | 0.06 |
| air quality | 0.14 | 0 | 0.002 ** | 0.05 |
| adjust. of furniture | 0.11 | 0 | 0.095 | 0.03 |
| visual comfort | 0.04 | 0 | 0.732 | 0.01 |
| visual privacy | 0.12 | 0 | 0.19 | 0.02 |
| **temperature** | **0.51** | **1** | **<0.001*****| **0.14** |
| noise | -0.08 | 0 | 0.223 | -0.02 |
| sound privacy | -0.02 | 0 | 0.876 | 0 |

[a] Metrics used for comparison include: difference in mean (ΔM) and median (ΔMdn); statistical significance of the difference (p-value), and effect size Spearman's ρ

### 3.2 Temperature satisfaction in radiant and all-air buildings

In Figure 1, we show the distribution of occupant responses for temperature satisfaction. This graph does not consider the difference between buildings but aggregates all individual responses. If we cluster positive votes, we observe that the 58% of the occupants are satisfied with radiant systems vs. 45% with all-air systems. If we add neutral votes, we reach 69% satisfied occupants with radiant systems vs. 62% with all-air systems. In Figure 2, we show boxplots of temperature satisfaction for radiant and all-air systems. Both mean and median are higher in the case of occupants exposed to radiant systems.


*Figure 1: Bar chart showing the distribution of temperature satisfaction for the radiant and all-air subset*

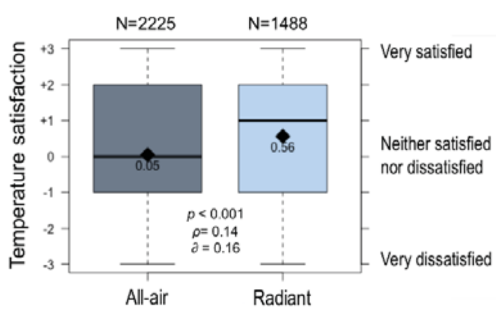


*Figure 2: Boxplot of temperature satisfaction (diamond dots represent mean values)*

We looked to the literature to find guidance on the interpretation of effect sizes. Cohen (Cohen 1988) 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 (Ferguson 2009) to more conservative thresholds of 0.2, 0.5 and 0.8, respectively, to prevent over-interpretation of effects (see Figure 3). Both authors commonly warn about the challenge of interpretation of effect sizes, which vary from one field to another. There are no interpretation schemes of effect sizes commonly used in our field.

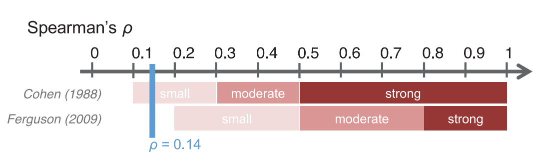


*Figure 3: Spearman's ρ effect size for the radiant vs. all-air comparison plotted against the interpretation thresholds according to Cohen and Fergusson*

To address this limitation and to keep the assessment and discussion into the context of buildings and occupant satisfaction, we decided to compare the effect size obtained for conditioning type (radiant/all-air) to the effect size obtained for other binary variables of our survey: type of ventilation (mixed-mode/mechanical), gender (male/female), distance to window (≤ or > 4.6 m.), and type of office (enclosed/open). Table 5 presents these results. The largest difference in effect size for temperature was found for gender (ρ=0.2), followed by conditioning type (ρ=0.14). The other variables showed low effect size comparatively. Karjalainen (Karjalainen 2012) 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 (odd ratios (OR): 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. If we apply to Karjalainen's results the threshold proposed by Ferguson (where OR ≤ 2 is a 'negligible'), then the effect of gender within his analysis remains below the minimum recommended value for a practically significant effect size. For our sample, gender just reaches the threshold of 'small' practical significance according the Ferguson's scale for Spearman's ρ; and the outcome for conditioning (radiant vs. all-air) is below gender (0.14 < 0.2). 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 satisfaction with temperature for different subgroups*

| Variables and sub-groups | ΔM | ΔMdn | p-value | Effect size (ρ) |
|---|---|---|---|---|
| Gender<br>*- male / female* | 0.74 | 1 | <0.001*** | 0.2 |
| Conditioning<br>*- radiant / all-air* | 0.51 | 1 | <0.001*** | 0.14 |
| Ventilation strategy<br>*- MM / MV* (a) | 0.09 | 1 | 0.139 | 0.02 |
| Distance to window<br>*- close / far away* (b) | 0.05 | 1 | 0.535 | 0.01 |
| Type of office<br>*- enclosed / open* | -0.02 | 0 | 0.898 | 0 |

(a) MM: mixed-mode and MV: mechanical ventilation;
(b) Close: window ≤4.6 m.; and far away: window >4.6 m.

In this study, the Cliff's ∂ explains the probability that a randomly selected observation from the radiant group has higher satisfaction than a randomly selected observation from the all-air group, minus its reverse probability (i.e. P(all-air < radiant) - P(radiant > all-air)). We decomposed this equation. Compared to a space using an all-air building, a person in a space using a radiant system has:

- 50% chance of having a higher temperature satisfaction rating
- 16% chance of having an equivalent rating
- 34% chance of having a lower temperature satisfaction rating.

Figure 4Figure 4 displays the distribution of these three probabilities. The Cliff's ∂ associated with this analysis is 0.16 (16% probability of higher temperature satisfaction for occupants exposed to radiant systems). We could not find references for interpretation for Cliff's delta values, and therefore this analysis should be viewed only as a useful means of interpreting the survey results.

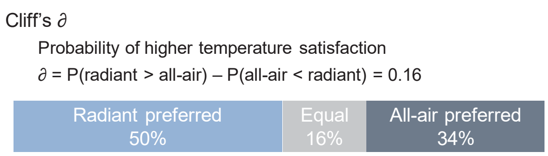


*Figure 4: Probability of higher temperature satisfaction for the radiant and all-air conditioning subsets*

### 3.3 Acoustic satisfaction in radiant and all-air buildings

Buildings using radiant systems are associated with lower acoustical quality; this is particularly the case for radiant in-slab systems (ESS and TABS types) due to large exposed acoustically reflective (i.e., 'hard') surfaces (Bauman et al. 2011). Based on Table 4, neither of the two acoustic categories (noise and sound privacy) showed statistically significant and practically 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 (Frontczak et al. 2012; Kim et al. 2013). To address this complexity, we used a mixed-effect model with 'type of office' (cubicles with high partitions, cubicles with low partitions, enclosed private office, enclosed shared office, open office with no partitions) as the random effect. We also distinguished in-slab (ESS & TABS) from panel (RCP) types of radiant systems. 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 favour of in-slab radiant systems compared to all-air systems. The random effect reached 21% suggesting that the large spread in the variance can be described by 'between office type' differences. 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 the most challenging aspect in regard to occupant satisfaction in buildings, for both radiant and all-air systems.

### 4. STUDY LIMITATIONS

The buildings used for this study were selected following the methodology detailed in section 2.2. Yet, the data available for the radiant subset was limited due to the general lack of buildings with radiant systems in North America. We sampled the all-air buildings data from a larger dataset based on characteristics that followed the radiant building's demographical and physical characteristics. Overall, the buildings of this study (both conditioning types) show a higher IEQ than 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 buildings and 34 all-air buildings, with 1,645 and 2,247, occupant responses, respectively. While this is a large sample size, it is not a randomized statistically-representative sample, which is a limitation of the study.

We could not find effect size interpretation thresholds that were representative of our field in existing publications. Our paper includes an analysis on effect size interpretation thresholds. This analysis should be seen as a precedent for discussion. Further research in this area can yield a different conclusion as to the practical significance of the observed and reported effect sizes.

### 4. CONCLUSION

We used the CBE IEQ occupant survey to compare occupant satisfaction in radiant and all-air conditioned buildings. This comparison involved 1,645 respondents from 26 buildings with radiant systems and 2,247 respondents from 34 buildings with all-air systems. The analysis showed that radiant and all-air conditioned spaces have equal IEQ, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings. From this dataset, a person has a 50% chance of experiencing higher temperature satisfaction in a space using a radiant system compared to an all-air system. The reverse probability reaches 34%, and there is a 16% chance for the two systems to bring equal satisfaction. We observed equal acoustic satisfaction (noise and sound privacy) in radiant and all-air systems, disproving some commonly held biases against radiant systems. Acoustic quality remains the most challenging aspect in regard to occupant satisfaction in buildings (lowest scores from all the categories surveyed).

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