Adaptive thermal comfort for resilient office buildings

Maureen Trebilcock-Kelly, Jaime Soto-Muñoz, Laura Marín-Restrepo
Universidad del Bío-Bío, Avda Collao 1202, Concepción, Chile
mtrebilc@ubiobio.cl

Abstract. New challenges for delivering more resilient and less energy-dependent office buildings require a better understanding of thermal comfort in different contexts and opportunities for adaptation. This study aims to determine comfort temperatures in 18 office buildings located in two Chilean cities. The methodology was based on a longitudinal fieldwork during 1 day in winter, spring and summer at each building, collecting data from surveys to the occupants and measurements. The results showed that comfort temperature varied consistently between both contexts and between different seasons, with wider seasonal variation of comfort temperatures in buildings where occupants are allowed to operate windows.

1. Introduction
Contemporary office buildings have been designed to provide high comfort standards for the occupants. The search for a definition of comfort standards has led researchers to carry out field work to establish comfort temperature based on the perception of users in real occupation conditions and not on arbitrary criteria [1]. People from different cultures and climates consider themselves to be comfortable in a wide range of temperatures, mainly related to the outdoor temperatures that are usual for them, according to the adaptive comfort model [2]. This approach is based on the adaptive principle: “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [3]. This work was complemented by other authors who established that the perception of comfort of people differs between different climates [4] and that the occupants of air-conditioned buildings have different "expectations" from those who occupy buildings ventilated naturally [5]. This adaptive thermal comfort model [2] [3] values diversity and considers long term adaptation as a gradual loss of the human response to repeated thermal stimulation, and can be either physiological, psychological or behavioral [4].

In recent years, the study of thermal comfort in relation to contextual, typological and cultural particularities has taken on special relevance. Several authors have discussed the thermal comfort criteria against the predictions of climate change, the challenges of energy efficiency and low greenhouse gas emissions, which is expected to face architects designing more resilient buildings, which can adapt in a better way to the requirements of its occupants [6] [7]. According to this, it is important to generate new knowledge about the thermal comfort of the occupants of office buildings in Chile that allow orienting regulations that promote the flexibility of the design and operation of the buildings, and the adaptability of the occupant.

In Chile, new standards and guidelines [8] define indicators and thermal comfort standards in office buildings, which have been adopted by the public sector. However, these standards have not been contrasted with empirical experiences that raise the perception of the occupants in the local context. This paper presents the results of a study that aims to determine comfort temperatures in office buildings located in two Chilean cities from the perspective of their occupants and compares these results with the opportunities for adapting the thermal environment that the buildings provide to them.
2. Methodology
The methodology was based on a longitudinal fieldwork carried out in 2017-2018 in 9 office buildings located in the city of Santiago and 9 office buildings located in the city of Concepción. These two cities have different climatic conditions: Santiago (33°S) has a Mediterranean-continental climate (Koppen Csc) with average temperatures varying from 13.4°C to 30.1°C in January and varying from 1.3°C to 14.3°C in July. Concepción (37°S) has a Mediterranean-oceanic climate (Koppen Csb) with average temperatures in January varying from 10.9°C to 22.8°C and average temperatures in July varying from 5.8°C to 13.2°C. Therefore, Santiago has much higher temperatures in summer than Concepción, with an extended cooling season. Each case study was identified with a capital letter: cases "A" to "I" are located in Concepción, while the cases "J" to "S" are located in Santiago (Figure 1). The study covered 1055 participants, with a set of 5331 votes.

Figure 1. Case studies: office buildings located in Concepción (top) and Santiago (bottom)

The fieldwork included three campaigns in each building during a single day in winter, spring and summer. At each visit, the occupants of the building were surveyed three times per day (morning, midday and afternoon) to determine their thermal sensation, thermal preference and thermal acceptability. These right-now surveys were based on responses on a scale between -3 and +3 for thermal sensation, with 0 as neutral temperature; and based on a scale of -2 to +2 in thermal preference, with 0 as "no change" preference. The questionnaire also included questions regarding opportunities given by the building to the occupants for adapting their thermal environment in terms of window opening, adjusting shading devices, operating personal comfort devices (fans or heaters) and adjusting the temperature setpoint of the HVAC system. In addition, the fieldwork also comprised a one-time questionnaire that was applied in spring and that looked generally at the satisfaction of the occupants with the indoor environment in both winter and summer conditions.

In addition to the application of the questionnaire, the fieldwork also involved simultaneous measurements of internal ambient variables using a Delta Ohm HD32.3 instrument that registered dry bulb temperature (Ta), globe temperature (Tg), relative humidity (RH) and air velocity (Va) at 1 minute intervals (Table 1). The equipment was installed at the beginning of the working day of each building (usually 8:00AM) and removed at the end of the afternoon surveys. There were 7 available devices that were distributed in the corresponding building in fixed spots across the office spaces.

Table 1: Characteristics of the measuring equipment

| Probe                      | Sensor type     | Measuring range | Resolution | Accuracy     |
|----------------------------|-----------------|-----------------|------------|--------------|
| Dry bulb temperature (Ta)  | Pt100           | -40 to 100°C    | 0.1°C      | ±0.1°C       |
| Globe temperature (Tg)     | Pt100           | -10 to 100°C    | 0.1°C      | ±0.1°C       |
| (globe therm Ø150mm)       |                 |                 |            |              |
| Relative air humidity (RH) | Capacitive sensor | 5-98%          | 0.1%       | ±2%          |
| Air velocity (Va)          | NTC 10Kohm      | 0.05 to 5 m/s   | 0.01 m/s   | ±0.05 m/s (0 to 1 m/s) ±0.15 m/s (1 to 5 m/s) |
3. Comfort temperature

Figure 2 (top graph) shows average operative temperatures at each case study during the three seasons, which remain within a fairly regular range; between 21°C and 25°C during the occupied period, with some observable differences between winter, spring and summer.

The thermal sensation vote derived from the surveys is also illustrated in the mid-graph, where thermal sensation in winter tends to vary from neutral (0) towards slightly warm (+1), while the thermal sensation in summer tends to vary from neutral (0) towards slightly cool (-1). This represents a positive response from the occupants to the thermal indoor environment since in the summer season the neutral to slightly cool thermal sensation is associated with comfort, and the opposite occurs in winter.

Comfort temperature was calculated based on Griffiths method [9] that relates the average operating temperature with the average thermal sensation vote based on the perception of the occupants. The regression coefficient considered was G=0.5 as stipulated by [2]. The results are presented in the bottom

Figure 2. Average operative temperature (top), average thermal sensation vote (middle) and average comfort temperature (bottom) at each office building
graph showing that comfort temperature clearly varies along the season, with winter comfort temperatures between 20ºC and 22.7ºC amongst different cases; between 20.83ºC and 23.87ºC in spring; and between 21.68ºC and 24.66ºC in summer. These results are also consistent with the operative temperatures, confirming that occupants tend to adapt to indoor thermal conditions.

The statistical analysis was carried out using the software SPSS. In order to compare the differences between two groups, the independent t-test was used with bootstrap confidence intervals. For more than two groups, the one-way ANOVA was applied, and Welch’s F is reported. The significance level was defined as \( p < 0.05 \).

Figure 3 shows that comfort temperatures vary systematically not only through the seasons, but also within each climate context. The difference of 1ºC (BCa 95% CI [1.18, 0.87]) between comfort temperature in the office buildings located in Concepcion and those located in Santiago was significant, \( t(3986.89) = -11.740, p < 0.001 \), and similar across seasons. Likewise, comfort temperatures were significantly different by season both in Concepción: 20.88ºC-21.79ºC-23.09ºC-23.09ºC, \( F(2, 1338.71) = 96.54, p < 0.001 \), and in Santiago: 21.97ºC-22.77ºC-24.04ºC, \( F(2, 2044.05) = 163.15, p < 0.001 \).

![Figure 3. Average operative temperature and comfort temperature (ºC)](image)

4. Occupants’ adapting opportunities

The second stage of analysis looked at the buildings in terms of the opportunities for thermal adaptation given to their occupants based on the responses to the questionnaires. The adapting opportunities included those related to the design of the building, such as operable windows that allow for natural ventilation, as well as solar devices and blinds that can be operated by the occupants for thermal or lighting control. The other group of adapting opportunities relate to building technologies, such as thermostats and individual fans and heaters.

Figure shows that operable windows are much more common in office buildings in Concepción than in Santiago, as 48.6% of the occupants perceive that they have the opportunity to open/close a window during the surveys, compared to only 18.5% in Santiago. This difference, 30%, BCa 95% CI [27.4%, 32.8%], was significant \( t(4105.6) = 24.03, p < 0.001 \). On the other hand, cases in Santiago offer significantly more opportunities for setting the thermostat than cases in Concepción, around 17% (BCa 95% CI [14.7%, 19.7%]), \( t(5119.41) = 13.165, p < 0.001 \). This fact suggests that generally, buildings in Concepción rely more on passive strategies while buildings in Santiago rely on active technologies for adapting the thermal environment. However, the findings show that there is no correlation between the adapting opportunities given by the building and the thermal acceptability of the occupants, which remain fairly stable among the cases. The higher correlation was found between the opportunity for setting the thermostat and the satisfaction with the thermal environment in winter as responded by the occupants in the one-time questionnaire.
Figure 4. Opportunities given to the occupants for adapting the thermal environment

Finally, Figure 5 presents comfort temperatures arranged by the cases with more opportunities for opening/closing windows on the left and those with less than 20% opportunities on the right. It is interesting to note that the variation of comfort temperatures between the seasons (summer and winter) is wider in those cases with more opportunities for window opening (mean 2.5K) than in those office buildings that are much more sealed to the outdoor, particularly those with less than 20% of opportunity (mean 1.6K). This difference, 0.86K, BCa 95% CI [0.37, 1.37] was significant, t(12.425)=3.107, p=0.009.
Figure 5. Comfort temperature of the case studies organised by opportunities for opening/closing windows

5. Conclusions
The findings of this study show that comfort temperature in office buildings located in these two Chilean cities vary according to the climatic contexts and across the different seasons. However, they generally remain within the comfort range commonly found in the literature, which contrasts with findings of similar studies in the country covering school buildings and housing where occupants tend to adapt to much lower temperatures in winter. These findings suggest that office workers tend to be much more demanding with their thermal environment in this context. The cases showed varied opportunities for thermal adaptation given to the occupants. In Concepción, buildings tend to be more “passive” with operable windows and adjustable shading devices, whereas in Santiago, buildings tend to be more “active” with more opportunities for adjusting the thermostat of the HVAC. Only this last control opportunity showed high correlation with the general satisfaction of the occupants with the building in winter, suggesting that there is little correlation between thermal acceptability and satisfaction and the opportunities given by the building for adaptation.

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