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Building Research & Information

ISSN: 0961-3218 (Print) 1466-4321 (Online) Journal homepage: http://www.tandfonline.com/loi/rbri20

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To cite this article: Rick Kramer, Lisje Schellen & Henk Schellen (2018) Adaptive temperature limits for air-conditioned museums in temperate climates, Building Research & Information, 46:6, 686-697, DOI: 10.1080/09613218.2017.1327561

To link to this article: https://doi.org/10.1080/09613218.2017.1327561

Published online: 01 Jun 2017.

BRI
BUILDING RESEARCH & INFORMATION
2018, VOL. 46, NO. 6, 686–697
https://doi.org/10.1080/09613218.2017.1327561
Routledge Taylor & Francis Group

RESEARCH PAPER

Adaptive temperature limits for air-conditioned museums in temperate climates

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ABSTRACT
Indoor temperature (*T*) and relative humidity (RH) are important for collection preservation and thermal comfort in museums. In the 20th century, the notion evolved that *T* and RH need to be stringently controlled, often resulting in excessive energy consumption. However, recent studies have shown that controlled fluctuations are permissible, enabling improved energy efficiency. Consequently, the thermal comfort requirements are increasingly important to determine temperature limits, but knowledge is limited. Therefore, a thermal comfort survey study and indoor measurements were conducted at Hermitage Amsterdam museum in Amsterdam, the Netherlands for one year, including: (1) monitoring of existing conditions ($T = 21$°C, RH = 50%); and (2) an intervention in which *T* is controlled based on an adaptive comfort approach ($T =$ 19.5–24°C, RH = 50%). The results show that the thermal comfort of the existing conditions is far from optimum; visitors feel too cool in summer and slightly too warm in winter. The adaptive temperature limits were developed to improve thermal comfort significantly without endangering the collection, thereby saving energy. Furthermore, facilitating visitors to adapt their clothing may contribute to enlarging the temperature bandwidth and improve (individual) thermal comfort.

KEYWORDS
adaptive comfort; energy conservation; museums; occupants; temperature variation; thermal comfort

Introduction

Indoor climate conditions are important for collection preservation and thermal comfort inside museums. During the 20th century, the indoor ambient air temperature (T_{air}) and relative air humidity (RH_{air}) have been controlled with increasing precision for collection preservation (Brown & Rose, 1996). Established ideas surrounding indoor climate conditioning can be crystallized into the phrase 'the more stable, the better'. However, studies focusing on energy efficiency show that stringently conditioning the indoor climate of museums results in excessive energy consumption (Ascione, Bellia, Capozzoli, & Minichiello, 2009; Kramer, Schellen, & Van Schijndel, 2016; Mueller, 2013), particularly if a museum is housed in a historic building or structure (Ascione, de Rossi, & Vanoli, 2011; Papadopoulos, Avgelis, & Santamouris, 2003; Rota, Corgnati, & Di Corato, 2015; Zannis et al., 2006). Moreover, maintaining a constant room temperature during the year in museums located in climate regions with significant seasonal outdoor climate fluctuations may result in thermal discomfort (de Dear & Brager, 1998; Kramer, Maas, Martens, van Schijndel, & Schellen, 2015).

At the beginning of the 21st century, when energy efficiency became more important with respect to increasing sustainability and decreasing energy costs, notions surrounding indoor climate conditioning in museums began to change from strict conditioning to more reasonable (Dardes & Staniforth, 2015), *i.e.* taking the collection needs as a reference instead of the heating ventilation and air-conditioning (HVAC) capabilities. Recent studies have found that many objects tolerate a larger T_{air} and RH_{air} fluctuations than expected (*e.g.* Ashley-Smith, Umney, & Ford, 1994; Bratasz, Kozlowski, Kozlowska, & Rivers, 2008; Dionisi Vici, Mazzanti, & & Uzielli, 2006; Erhardt, Tumosa, & Mecklenburg, 2007; Lukomski, 2012). For example, Martens (2012) conducted a large-scale experimental study including 21 museums in the Netherlands. Collection degradation risks from the measured indoor climates were assessed

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for several artefacts using damage functions for biological, chemical and mechanical degradation. The results reveal that collection risks in museums with a low level of indoor climate control are not necessarily larger compared with museums with a high level of indoor climate control. Controlled seasonal fluctuations were proven to be a better choice than a standard set-point for the whole year in many of the museums studied. Hence, employing a range of permissible indoor climate conditions, instead of fixed set-points, has become a viable means of balancing collection conservation and energy consumption (*e.g.* Ankersmit, 2009; Kramer, Maas, et al., 2015; Michalski, 2007). However, the permissible temperature (T) range regarding collection conservation is expected to be larger than the range acceptable for the thermal comfort of visitors and staff, *e.g.* as indicated by Kramer, Maas, et al. (2015). (Note that literature on collection requirements does not consistently differentiate between T_{air} and T_{op} (operative T).) For example, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) climate classes for museums, galleries, archives and libraries (ASHRAE, 2011), the most strict class (AA) specifies short fluctuations of ±2°C with additional seasonal set-point adjustments of ±5°C. For loan exhibitions with a starting-point of 21°C, this results in a range of 14–18°C in winter and 24–28°C in summer. Hence, further knowledge is necessary concerning permissible temperature limits regarding thermal comfort in museum environments.

Standards, *e.g.* EN-ISO 7730 (EN-ISO, 7730, 2005) and ASHRAE Standard 55 (ANSI/ASHRAE, 2013), prescribing thermal comfort requirements are mainly based on research in office environments. These standards use Fanger's predicted mean vote (PMV) model to determine 'optimal' thermal conditions (Fanger, 1970). This model reflects the heat balance for an average person based on uniform environmental parameters, activity level and clothing insulation. The model aims for constant indoor climate conditions without permissible fluctuations. However, results from a large-scale field study reveal that satisfaction with the thermal environment does not mean that this environment has to be controlled at a constant T_{op} (de Dear & Brager, 1998). These findings have led to an adaptive thermal comfort approach and generated a significant paradigm shift away from a heat balance-based approach (de Dear et al., 2013). The adaptive approach accounts for the fact that humans adapt to seasonal variations in environmental conditions. Moreover, the adaptive approach implicitly takes into account the effects of expectations towards a thermal environment. Therefore, the application of the adaptive thermal comfort approach results in more varied indoor thermal climates depending on outdoor conditions (de Dear & Brager, 1998). Together with the possibility of enlarging temperature bandwidths regarding collection preservation, applying an adaptive approach in museum environments may result in improved thermal comfort and contribute to improving energy efficiency.

Recent studies suggest that there are significant differences among individuals regarding thermal preferences due to age, gender and body composition (Kingma & van Marken Lichtenbelt, 2015; Schellen, Loomans, de Wit, Olesen, & van Marken Lichtenbelt, 2012; Schellen, van Marken Lichtenbelt, Loomans, Toftum, & de Wit, 2010). As the museum visitor population is far from homogeneous and may even differ more than typical office worker populations, it is relevant to take this into account. Moreover, under the assumption that office workers are mainly seated (activity level ≈ 1.1 met) and museum visitors alternate between standing relaxed and walking about (mean activity level ≈ 1.5 met), it is important to take into account that the activity level in a museum environment is elevated compared with office environments. As this is an important factor for human heat balance, its incorporation is relevant.

The objective of this study is twofold: (1) to assess thermal comfort perception in a strictly conditioned museum environment without seasonal variations; and (2) to develop operative temperature limits according to an adaptive thermal comfort approach, allowing for more seasonal variation. Therefore, a case study at Hermitage Amsterdam museum in Amsterdam, the Netherlands, was conducted comprised of surveys, indoor climate measurements and outdoor climate measurements. Furthermore, an intervention was performed to investigate the effects of implementing an adaptive temperature control strategy on indoor environmental conditions and thermal comfort. In 2015, 30 surveys were collected weekly, resulting in a total of 1248 questionnaires (509 questionnaires during the existing conditions and 739 questionnaires during the intervention).

Methodology

Case study: Hermitage Amsterdam

Hermitage Amsterdam is a sister museum of The State Hermitage Museum in St Petersburg, Russia, located in Amsterdam. It has no collection of its own, but displays exhibitions on loan. The artworks mainly belong to the Hermitage Museum in St Petersburg, but also to other museums. Hermitage Amsterdam is housed in a late 17th-century building, and the most recent renovation

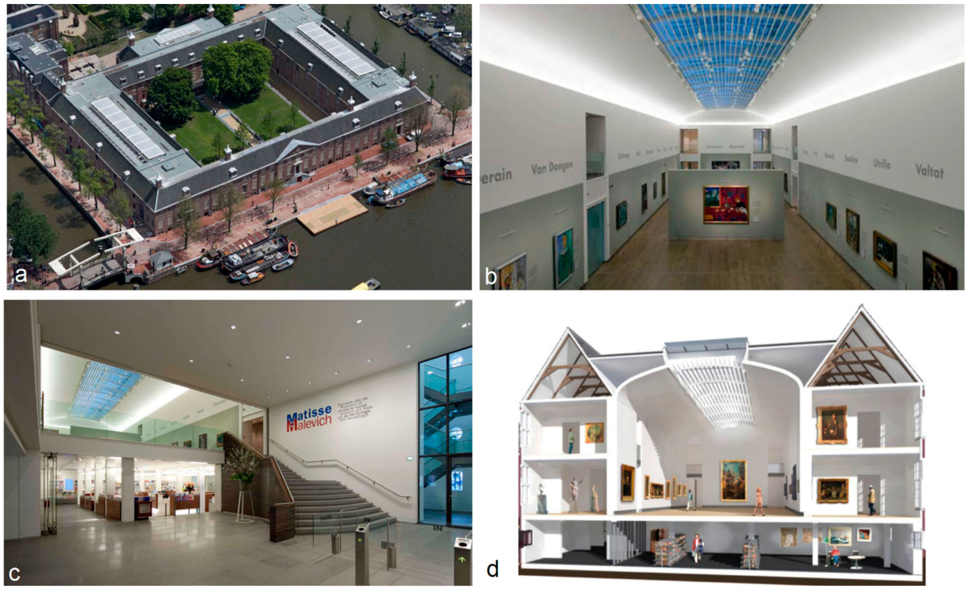


Figure 1. (a) Aerial view of Hermitage Amsterdam; (b) one of the two main exhibition rooms with a large glass roof; (c) the entrance stair from the lobby to the main exhibition room with an air curtain to reduce air exchange; and (d) cross-section of one side of the building showing the main exhibition room and adjacent cabinets. Source: Kramer, van Schijndel, and Schellen (2016).

dates from 2007–09 when the building was transformed into a state-of-the-art museum (Figure 1). The historic building envelope was conserved and insulated from the inside. An all-air heating, ventilation and air-conditioning (HVAC) system was installed to condition the exhibition areas, and floor heating was installed in non-exhibition areas, such as the restaurant and foyer. With the goal of a stable museum environment, the indoor climate specifications employed, without seasonal adjustment, are 21°C and 50% RH with a deadband of ±0.5°C.

Figure 1(a) shows the layout of the building. Its historical appearance was preserved by restoring the facade, but all remaining parts of the building were rebuilt to accommodate adequately the museum's exhibitions. The building has a symmetrical floor plan: two identical exhibition wings can be recognized by their glass skylights on the left and right side roofs in Figure 1(a).

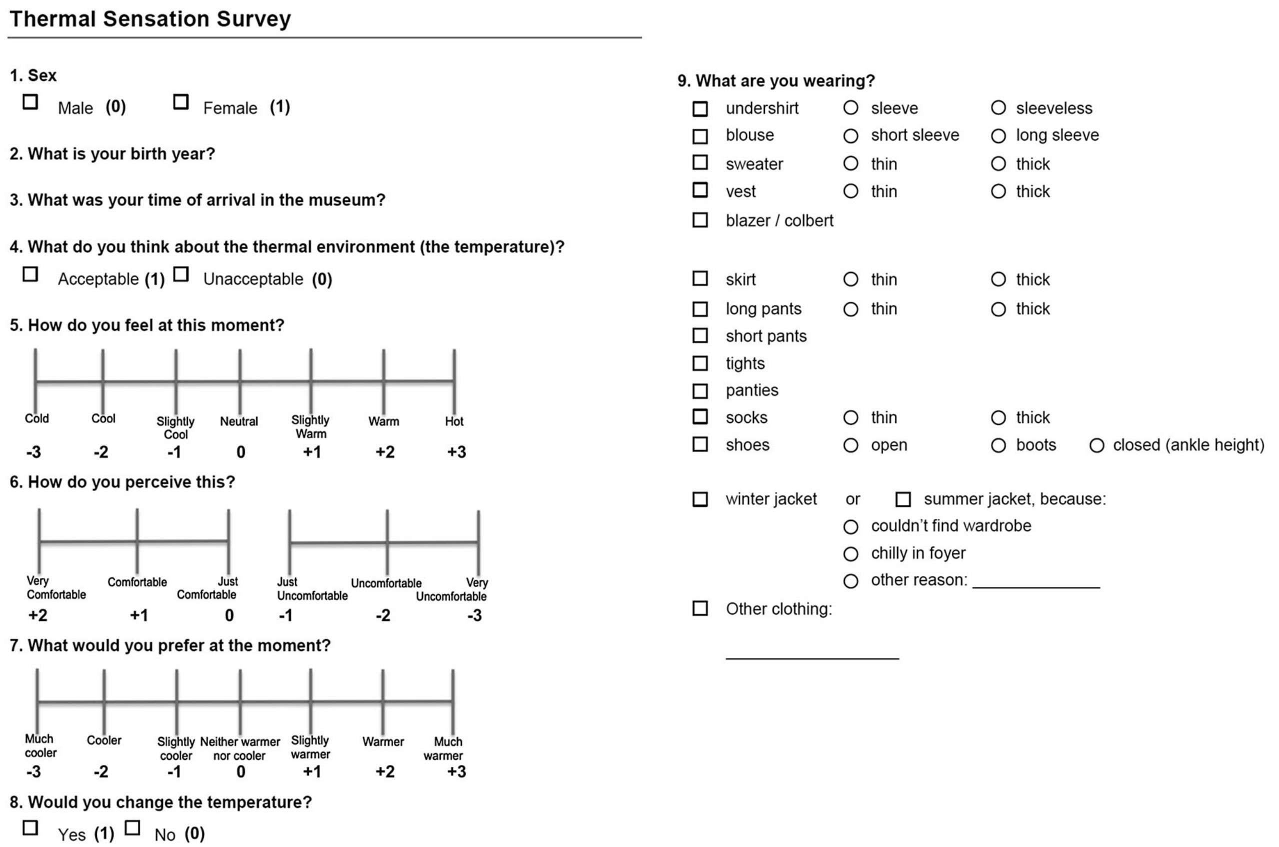
This study focuses on 'de Keizersvleugel', the exhibition wing shown on the right side of Figure 1(a). The exhibition area consists of the main hall (Figure 1(b)) and adjacent cabinets (Figure 1(d)). Visitors enter the exhibition area via a stairway from the foyer (Figure 1 (c)). The ceiling of the main exhibition hall consists in part of a large glass roof with interior sun blinds that are almost permanently closed. An air curtain has been applied to limit air exchange between the main exhibition room and the foyer.

The museum is open seven days per week from 10:00 to 17:00 hours, and has welcomed 7000–11,000 visitors per week depending on the exhibition. Measurements for the current study were conducted over nearly one year without changes to the exhibition, resulting in a stable weekly visitor profile. Most individuals visited the museum on Sunday, Tuesday and Wednesday, while the least number attended on Monday.

Data acquisition

The current study was conducted between February and December 2015, alternating between existing conditions and the intervention. Data acquisition comprised surveys (subjective) and indoor climate measurements (objective). Surveys were conducted on Wednesdays and Thursdays between 11:00 and 14:00 hours. At least 30 surveys were collected each survey day. The surveys were collected in the cabinets on the second floor in 'de Keizersvleugel' (Figure 3, location Q). This location was most suitable because most museum visitors had spent more than 30 minutes inside upon reaching this location. Moreover, seats provided in the cabinets (rooms) gave a practical advantage, certainly for older adults. Surveys were provided in both Dutch and English. Figure 2 shows the survey, including the numerical transcription used for the statistical analysis.

The survey included nine questions concerning gender, age, time in the museum, acceptability of the thermal indoor environment, thermal sensation, thermal comfort, thermal preference, desire to change the temperature and clothing level. Clothing level was determined based on participants' responses to the survey. The transcription to Clo-value was based on numerical values


Thermal Sensation Survey

1. Sex
☐ Male (0) ☐ Female (1)

2. What is your birth year?

3. What was your time of arrival in the museum?

4. What do you think about the thermal environment (the temperature)?
☐ Acceptable (1) ☐ Unacceptable (0)

5. How do you feel at this moment?
Cold -3, Cool -2, Slightly Cool -1, Neutral 0, Slightly Warm +1, Warm +2, Hot +3

6. How do you perceive this?
Very Comfortable +2, Comfortable +1, Just Comfortable 0, Just Uncomfortable -1, Uncomfortable -2, Very Uncomfortable -3

7. What would you prefer at the moment?
Much cooler -3, Cooler -2, Slightly cooler -1, Neither warmer nor cooler 0, Slightly warmer +1, Warmer +2, Much warmer +3

8. Would you change the temperature?
☐ Yes (1) ☐ No (0)

9. What are you wearing?
☐ undershirt ○ sleeve ○ sleeveless
☐ blouse ○ short sleeve ○ long sleeve
☐ sweater ○ thin ○ thick
☐ vest ○ thin ○ thick
☐ blazer / colbert

☐ skirt ○ thin ○ thick
☐ long pants ○ thin ○ thick
☐ short pants
☐ tights
☐ panties
☐ socks ○ thin ○ thick
☐ shoes ○ open ○ boots ○ closed (ankle height)

☐ winter jacket or ☐ summer jacket, because:
○ couldn't find wardrobe
○ chilly in foyer
○ other reason: ____________
☐ Other clothing:
____

Figure 2. Thermal sensation survey including the numerical transcription used for statistical analysis.

provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ANSI/ASHRAE, 2013).

Indoor measurements consisted of air temperature, radiant temperature (T_{rad}), relative air humidity and airspeed (V_{air}). Table 1 provides specifications concerning the measurement instruments employed. Indoor measurements were performed at a height of 1.7 metres, as recommended by ANSI/ASHRAE (2013). The sampling interval for the indoor measurements was 1 second. The indoor operative temperature was used for further analysis and calculated as the mean of the air temperature and the radiant temperature.

Outdoor air temperature and relative air humidity were acquired from the museum's weather station via the building management system. The sampling interval for the outdoor measurements was 16 minutes.

Table 1. Specification of instruments used for indoor climate measurements.

Variable	Range	Accuracy	Sensor
Air temperature, T_{air} (°C)	−80 to 150	±0.1	NTC type DC95
Radiant temperature, T_{rad} (°C)	−55 to 80	±0.05	NTC U-type
Air relative humidity, RH_{air} (%)	0–100%	±3	Humitter® 50YX
Airspeed, V_{air} (m/s)	0.05–5.0	0.02% ± 1.5%	SensoAnemo 5132SF

Monitoring and intervention

The study consists of two phases: a monitoring phase and an intervention phase to study the effects of a less strictly controlled indoor climate. Monitoring assessed the thermal comfort of visitors under the existing museum conditions with strict T and RH control. The set-points for T and RH for monitoring were 21°C and 50%. The number of test days per season was: four days in winter, four days in spring, five days in summer and two days in autumn.

During the intervention, the RH set-point was maintained at 50% and the T set-point was adjusted such that a mean thermal sensation vote (MTSV) of approximately 0.5 or −0.5 was to be expected with the help of the PMV model (Kramer, Schellen, & van Schijndel, 2015). The metabolic rate was assumed to be 1.5 met, and the clothing level was estimated using the equation provided by de Dear and Brager (1998) for HVAC buildings. The model relates the clothing level to the outdoor temperature. The T set-point was changed via the building management system one day before the intervention surveys to provide sufficient time for the indoor climate to stabilize.

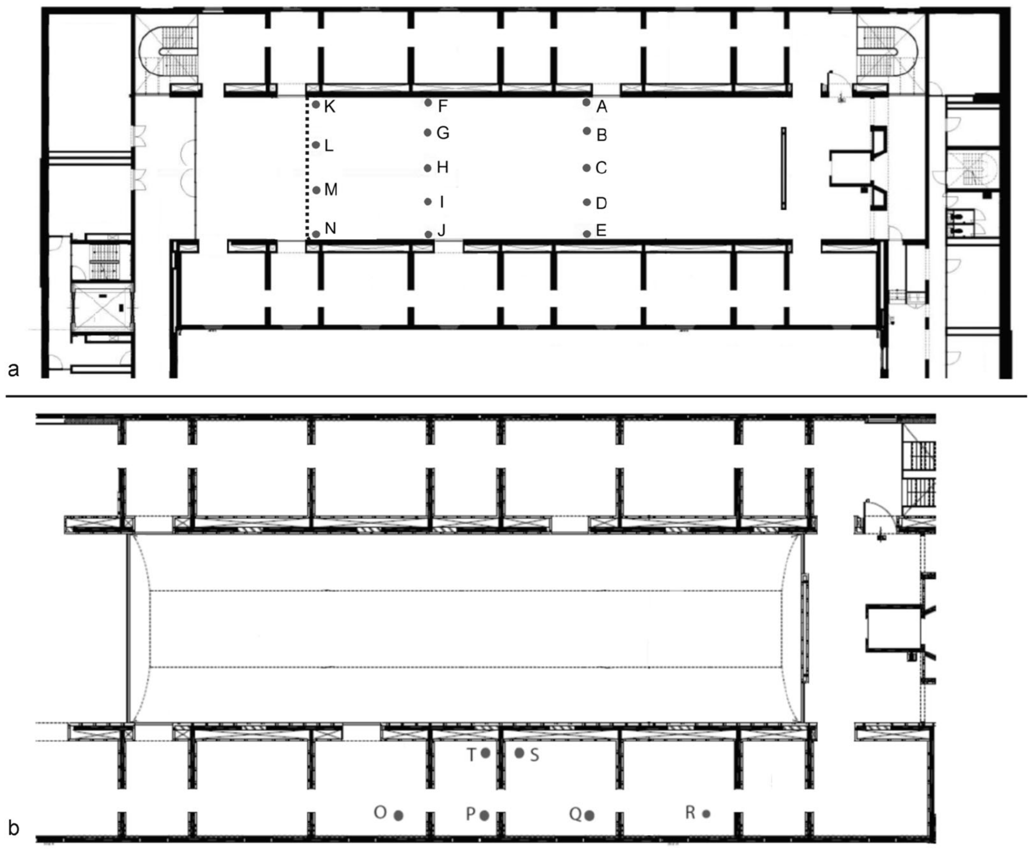


Figure 3. (a) Measurement positions located in the main exhibition hall; (b) measurement positions in the cabinets on the second floor. Measurement height = 1.7 m.

The number of test days per season was: two days in winter, six days in spring, eight days in summer and five days in autumn.

Statistics

For the statistical analyses, only participants who visited the museum for longer than 30 minutes were included to exclude transition effects from moving between outdoors and indoors. Moreover, incomplete surveys were excluded from the analyses. Differences between categories' means were assessed using an unpaired *t*-test. Linear regression analyses were used to construct adaptive temperature limits. Significant effects are reported for $p < 0.05$. Correlations between subjective and objective data columns were examined and considered relevant if larger than 0.3 (as recommended by Kenny, 1987, ch. 7). Since subjective responses have an ordinal nature, both Pearson (r) and Spearman (ρ) correlations were examined. While Pearson correlations can be used to detect linear relationships, Spearman correlations would have flagged any non-linear, but still monotonic, relations. For most cases that yielded relevant correlations, $r > \rho$ with a few cases where ρ was slightly larger. Hence, the reported correlations are only in terms of r. The commercially available software packages MATLAB Release 2015b (Mathworks Inc., Natick, MA, US) and PASW Statistics 23.0 (SPSS Inc., Chicago, IL, US) were used to analyse the data.

Development of temperature limits

For the development of operative temperature limits, thermal sensation and clothing level were related to a reference outdoor temperature ($T_{e,\text{ref}}$), calculated according to:

$$T_{\text{e,ref}} = \frac{T_{\text{e,i}} + 0.8T_{\text{e,i}-1} + 0.4T_{\text{e,i}-2} + 0.2T_{\text{e,i}-3}}{2.4}, \quad (1)$$

where $T_{e,i}$ is the average outdoor air temperature on the survey day; and $T_{e,i-1}$ is the average of the day before etc. The average is the arithmetic mean of the minimum and maximum outdoor air temperature of the given day. This reference outdoor temperature was proposed by van der Linden, Boerstra, Raue, Kurvers, and de Dear (2006) and is an implementation of the exponentially weighted running mean outdoor temperature by Nicol and Humphreys (2002).

Every survey day resulted in an MTSV, which is the average of all thermal sensation votes (TSV) for that day. The following MTSVs were used to construct the temperature limits $-0.1 < \text{MTSV} < 0.1$ to represent the neutral zone, $-0.6 < \text{MTSV} < -0.4$ for the lower limit, and $0.4 < \text{MTSV} < 0.6$ for the upper limit. The range between the lower and upper limit is considered to be the 90% acceptance class (Fanger, 1970). To determine the neutral temperature set-point (T_{neutral}) as a function of the reference outdoor temperature $T_{e\text{,ref}}$, operative indoor temperatures for the survey days that yielded an MTSV between −0.1 and 0.1 were plotted as a function of $T_{e\text{,ref}}$. Subsequently, univariate linear least squares regression was applied to find the linear relation between neutral temperatures and $T_{e\text{,ref}}$ and the coefficient of determination (R^2). This procedure was repeated to determine the linear relation of the upper and lower operative temperature limits as a function of $T_{e\text{,ref}}$.

Results

First, analysis results concerning the existing indoor environment are presented in which T and RH were controlled at 21°C and 50%. Then the results of the intervention study are presented in which T set-points were changed in a range of 19.5–24°C and RH was controlled at 50%.

Strictly conditioned museum environment

Indoor environmental conditions

During one of the survey days in September 2015, extensive indoor climate measurements were conducted on a measurement grid covering the entire main exhibition hall and the majority of cabinets on the second floor. Figure 3 shows the measurement positions (height 1.7 metres); Table 2 presents the results. Differences between air temperature and radiant temperature were minor due to the well-insulated building envelope, but significant (0.05 ± 0.08°C, $p = 0.04$). Furthermore, temperature differences between the measurement positions in the main hall were minor (0.34 ± 0.32°C) although significant (*e.g.* A:D, $p < 0.01$), showing a sufficiently homogeneous indoor environment. However, a slightly higher airspeed (+0.12 m/s) was measured at positions K, L, M and N in the main hall. A temporary wall (indicated by the dotted line) obstructed the normal circulation pattern of the air, but this does not affect the outcome of the study as the survey was conducted in the cabinets (rooms). Some significant temperature differences were recorded between the cabinets' window (positions O, P, Q and R) and internal wall sides (positions S and T): 1.18 ± 0.06°C, $p < 0.01$. Fluctuations over time were limited as indicated by the standard deviations (SDs) shown in Table 2 (the SD of measurement values during the measurement period of 5 minutes). The results verify that the indoor climate of the cabinets where surveys were conducted sufficiently represent the bulk of the indoor environment.

Table 2. Measurements of air temperature (T_{air}), radiant temperature (T_{rad}), relative air humidity (RH_{air}) and airspeed (V_{air}). The measurement time was 5 minutes per position with a sampling time of 1 second.

Position	T_{air} (°C)	T_{rad} (°C)	RH_{air} (%)	V_{air} (m/s)
A	20.7 ± 0.05	20.9 ± 0.03	48.8 ± 0.003	0.13 ± 0.04
B	20.8 ± 0.02	21.0 ± 0.01	48.2 ± 0.001	0.17 ± 0.05
C	20.9 ± 0.03	21.0 ± 0.01	48.1 ± 0.001	0.17 ± 0.04
D	21.0 ± 0.01	21.0 ± 0.01	47.8 ± 0.001	0.17 ± 0.05
E	21.0 ± 0.01	21.1 ± 0.01	47.8 ± 0.001	0.16 ± 0.05
F	21.0 ± 0.03	21.1 ± 0.02	47.8 ± 0.004	0.13 ± 0.06
G	21.2 ± 0.01	21.2 ± 0.01	47.6 ± 0.001	0.14 ± 0.05
H	21.1 ± 0.01	21.2 ± 0.01	47.5 ± 0.001	0.14 ± 0.05
I	21.1 ± 0.01	21.1 ± 0.01	47.5 ± 0.001	0.14 ± 0.06
J	21.1 ± 0.01	21.1 ± 0.01	47.6 ± 0.002	0.13 ± 0.06
K	21.1 ± 0.01	21.1 ± 0.01	47.3 ± 0.010	0.25 ± 0.07
L	21.2 ± 0.01	21.2 ± 0.02	47.0 ± 0.003	0.23 ± 0.07
M	21.2 ± 0.01	21.2 ± 0.01	47.0 ± 0.001	0.28 ± 0.08
N	21.1 ± 0.01	21.2 ± 0.01	46.8 ± 0.001	0.27 ± 0.07
O	20.6 ± 0.04	20.7 ± 0.09	44.0 ± 0.004	0.15 ± 0.05
P	20.5 ± 0.04	20.5 ± 0.01	44.0 ± 0.004	0.15 ± 0.06
Q	21.9 ± 0.23	21.9 ± 0.14	50.0 ± 0.006	0.10 ± 0.06
R	20.8 ± 0.02	20.7 ± 0.02	43.0 ± 0.001	0.15 ± 0.12
S	21.8 ± 0.01	21.9 ± 0.01	49.5 ± 0.001	0.12 ± 0.10
T	22.0 ± 0.01	21.9 ± 0.01	49.1 ± 0.001	0.09 ± 0.03

Note: Values are mean ± standard deviation (SD).

Figure 4 shows the mean indoor operative temperature as a function of the outdoor reference temperature ($T_{e\text{,ref}}$) during 1.5 hours of measurements per survey day. The results show that the indoor museum environment is strictly conditioned within a range of ±0.5°C around 21°C, irrespective of the season or outdoor climate conditions.

Subjective responses

Figure 5 shows TSVs collected under the strict existing conditions (indoor operative temperatures as depicted in Figure 4). The results show a significant correlation between thermal sensation and outdoor temperature ($r = -0.41$, $p < 0.01$). Compared with the mid-range of $T_{e\text{,ref}}$, *i.e.* in spring and autumn, the indoor temperature of 21°C is perceived as significantly warmer in the case of lower outdoor temperatures ($p < 0.05$) and significantly cooler in the case of higher outdoor temperatures ($p < 0.01$). This shows that maintaining the indoor temperature at 21°C for all seasons results in stronger discomfort in summer than in winter.

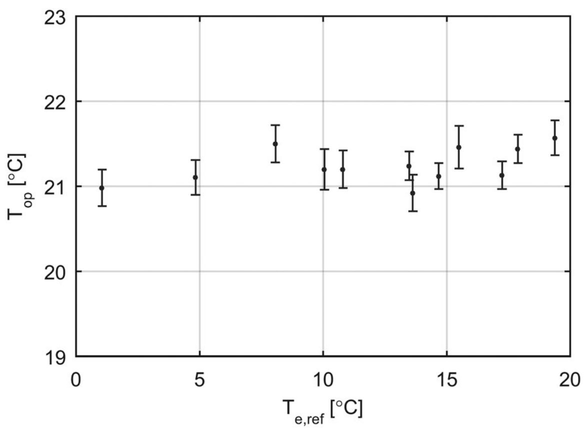


Figure 4. Mean indoor operative temperatures ± standard deviation (SD) as a function of the reference outdoor temperature during survey days. The temperature set-point was 21°C for all days. The measurement time was 1.5 hours per position with a sampling rate of 1 second.

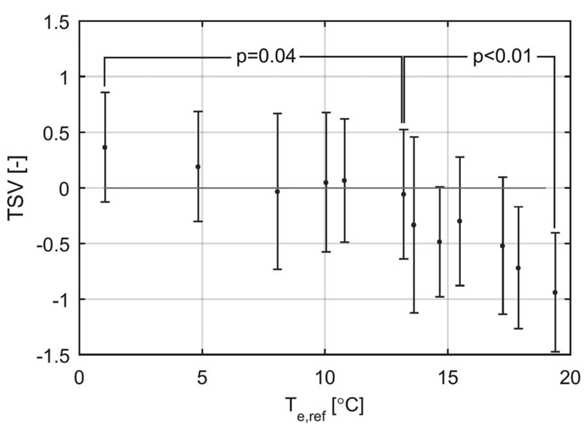


Figure 5. Mean thermal sensation votes (MTSVs) ± standard deviation (SD) as a function of the reference outdoor temperature during survey days. The temperature set-point was 21°C for all days (indoor temperatures are as shown in Figure 4).

Intervention

Indoor environmental conditions

Besides maintaining and assessing the existing indoor environment, an intervention study was performed in which the indoor temperature set-point was changed one day before the survey day to ensure a stable indoor climate during the surveys. The results of the intervention study were used to develop adaptive temperature limits. Figure 6 shows the resulting operative indoor temperatures as a function of $T_{e,\mathrm{ref}}$ covering a range of 19.5–24°C.

Subjective responses

Figure 7 shows TSVs of the intervention study as a function of (1) the reference outdoor temperature ($T_{e,\mathrm{ref}}$) and (2) the operative indoor temperature (T_{op}). The SD bars

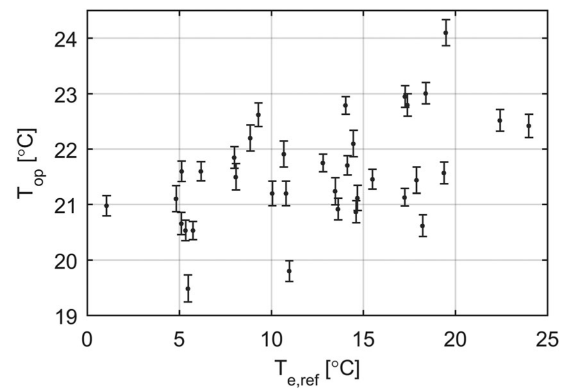


Figure 6. Mean operative temperatures ± standard deviation (SD) as a function of the reference outdoor temperature in the intervention study.

indicate large individual variations between respondents. The MTSVs of the survey days cover a small range from –1 (slightly cool) to 0.6 (neutral to slightly warm) because the museum staff allowed changing the *T* set-points in the rather strict range of 19–24°C. Individual responses, as indicated by the SD, range from –1.7 (slightly cool to cool) to 1.3 (slightly warm to warm).

Effects of gender and age on thermal comfort

As indicated above in the introduction, previous studies have shown that thermal comfort and related thermal behaviours depend on gender and age. Therefore, data have been categorized according to age and gender (Table 3). The results show that women felt slightly, but significantly, cooler than men ($p < 0.01$). All other observed differences shown in Table 3 are insignificant ($p > 0.05$); for example, the *t*-test revealed that differences in MTSV between age groups are statistically insignificant.

Furthermore, the Clo-value impacts thermal comfort. Therefore, the Clo-value was determined for each participant. Figure 8 shows the Clo-value related to $T_{e,\mathrm{ref}}$. Clothing level did not significantly differ between men and women ($p > 0.05$). A linear regression was applied to the mean Clo-values as a function of the $T_{e,\mathrm{ref}}$ of each survey day ($R^2 = 0.69$), resulting in the linear relationship Clo = 0.91–0.018 $T_{e,\mathrm{ref}}$ (Figure 8).

Construction of adaptive temperature limits

The operative temperatures of the survey days (T_{op}) were related to the reference outdoor temperatures ($T_{e,\mathrm{ref}}$) and related to the TSVs (Figure 9). The text labels show the MTSVs for the survey days. Although the data show large variances among individuals, the operative temperatures show a strong and significant linear relation

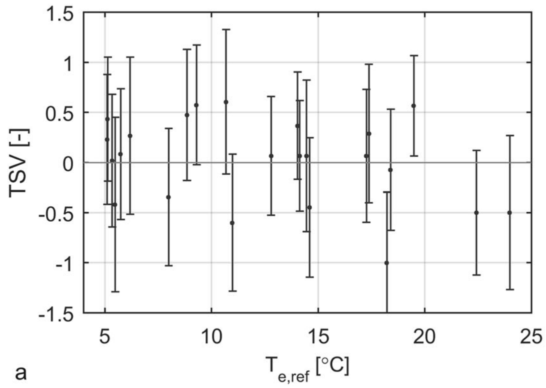


Figure 7. Mean thermal sensation votes (MTSV) ± standard deviation (SD) of the intervention study as a function of (a) the reference outdoor temperature and (b) the operative indoor temperature.

with the reference outdoor temperature for the upper temperature limit ($R^2 = 0.97$, $p < 0.05$), the neutral temperature ($R^2 = 0.84$, $p < 0.1$), and lower temperature limit ($R^2 = 0.95$, $p < 0.1$). Solid lines represent the linear regressions. However, note that data points for the upper limit are limited, whereas the neutral and lower limits are fitted to considerably more data points. The neutral temperatures are calculated according to:

$$T_{\text{neutral}} = 19.5 + 0.175\ T_{\text{e,ref}}. \tag{2}$$

Because the regressions resulted in nearly parallel limits, the final limits were determined by plotting the lower and upper temperature limits at exactly −1.2 and 1.2°C from the neutral temperatures (dotted lines). Hence, the upper temperature limit is calculated according to:

$$T_{\text{upper limit}} = 20.7 + 0.175\ T_{\text{e,ref}}, \tag{3}$$

and the lower temperature limit is calculated according to:

$$T_{\text{lower limit}} = 18.3 + 0.175\ T_{\text{e,ref}}. \tag{4}$$

Discussion and conclusions

The current study investigates visitors' thermal comfort perception in a strictly conditioned museum environment and explores the possibility of implementing adaptive temperature limits to promote energy efficiency and improve thermal comfort. Temperature limits that incorporate seasonal variations were developed and implemented in a case study at Hermitage Amsterdam. First, visitor thermal comfort under the existing strict conditions (21°C, 50% RH) were assessed. Subsequently, an intervention was conducted in which the indoor temperature was controlled as a function of the reference outdoor temperature (range = 19–23°C) and RH was maintained at 50%.

The results show that employing a fixed set-point of 21°C over the entire year without seasonal adjustments provides inadequate thermal comfort (Figure 5). Visitors perceived the indoor climate as slightly too warm in winter (TSV = 0.4 ± 0.51) and too cool in summer (TSV = −0.9 ± 0.52). The bias from thermal neutrality appears to be larger in summer than in winter, which can be explained by the fact that 21°C is closer to the comfort temperature in winter than in summer (Figure 9).

During the intervention, the T set-point was controlled as a function of the outdoor temperature

Table 3. Number of participants (N), mean thermal sensation vote (MTSV) and standard deviation (SD) categorized by gender and age.

	Men		Women	
Age (years)	N	MTSV	N	MTSV
< 30	62	0.16 ± 0.79	104	−0.08 ± 0.78
30–50	98	0.13 ± 0.79	121	−0.04 ± 0.93
51–70	196	−0.04 ± 0.95	378	−0.15 ± 0.96
> 70	89	0.06 ± 0.73	182	−0.07 ± 0.83

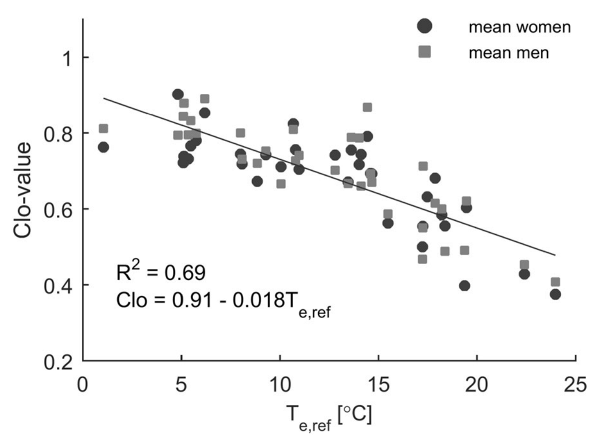


Figure 8. Clothing level of men and women related to the reference outdoor temperature.

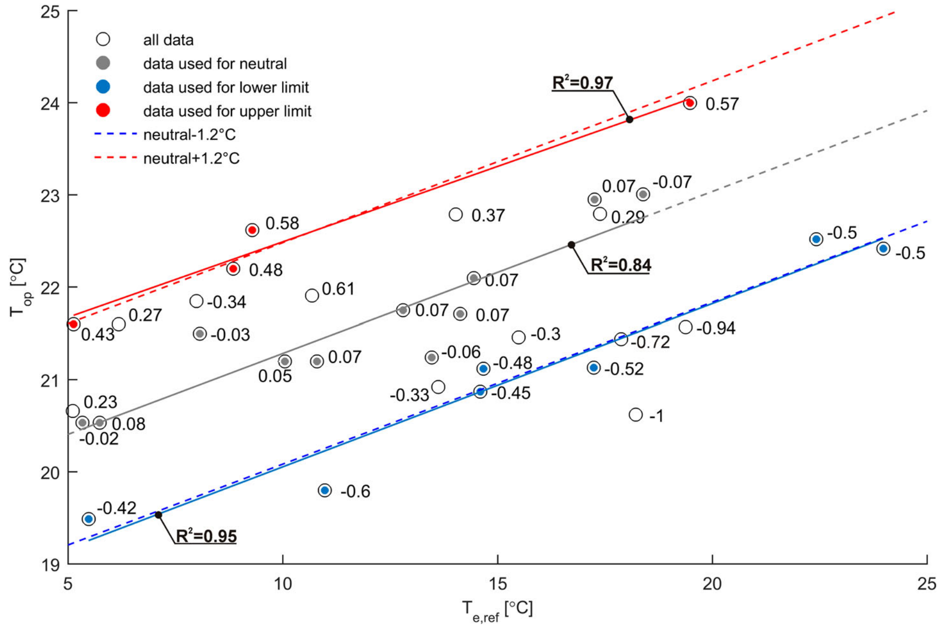


Figure 9. Construction of operative temperature limits according to 90% acceptance class. Solid lines represent linear regressions; dashed lines represent final limits (the neutral line is extrapolated; the dashed lower and upper limits are at ±1.2°C from the neutral).

according to the adaptive comfort approach. Museum staff's cautiousness towards the collection resulted in a limited range of tested operative temperatures: 19–24°C. Consequently, the range of TSVs is limited (–1.7 to 1.3). Therefore, the acquired data enable the construction of temperature limits according to the 90% acceptance class only. The lower limit corresponds to an MTSV of –0.5 and the upper limit corresponds to an MTSV of 0.5. It may be possible to apply the 80% acceptance class to most museums, and even preferred by some, as thermal comfort is not the main priority. Further research is required on the development and assessment of temperature limits yielding 80% acceptance.

Even new temperature limits – according to the 90% acceptance class – may significantly contribute to energy efficiency, as demonstrated by earlier studies (*e.g.* Ascione et al., 2009; Kramer, Maas, et al., 2015; Ryhl-Svendsen, Jensen, Larsen, & Padfield, 2010). Moreover, the energy-saving potential of the developed T limits was assessed in a year-long experimental study in the case study museum (Kramer, Schellen, et al., 2016). Controlling T according to the developed adaptive temperature limits and controlling RH between 45% and 55%, *i.e.* ASHRAE's museum climate class AA, results in an annual energy reduction of 49% compared with the existing indoor climate conditions (21°C, 50% RH).

Table 4 compares the linear comfort equation ($a + bx$) and permissible T range (upper and lower limits) found in this study with those in literature and standards. The permissible temperature range found in this study, neutral ±1.2°C, is equal to the range applicable for HVAC buildings, which may be expected since the case study museum is fully air-conditioned. However, the linear relation found in the current study shows a larger permissible variation with the outdoor climate: $a = 0.175$ compared with 0.11 in van der Linden et al. (2006) and $a = 0.04$ in de Dear and Brager (1998). However, a

Table 4. Equations for $T_{neutral}$ and temperature ranges according to the 90% acceptance class.

	Equation for $T_{neutral}$	90% acceptance class (°C)	Natural ventilation (NV) / heating, ventilation and air-conditioning (HVAC)
This study	$19.5 + 0.175\ T_{e,ref}$	±1.2	HVAC
van der Linden et al. (2006)	$21.5 + 0.11\ T_{e,ref}$	±1.2	HVAC
ASHRAE RP884 (de Dear & Brager, 1998)	22.6 + 0.04 ET*	±1.2	HVAC
ASHRAE RP884 (de Dear & Brager, 1998)	18.9 + 0.255 ET*	±2.5	NV
ASHRAE Standard 55 (ANSI/ASHRAE, 2013)	$17.8 + 0.31\ T_{month}$	±2.5	NV
EN-15251 (CEN, 2007)	$18.8 + 0.33\ T_{e,ref}$	±3.0	NV

Note: ET* = Effective temperature, an updated version of the earlier ET, see ASHRAE RP884.

direct comparison to the latter is difficult due to the use of mean outdoor ET* as reference outdoor temperature. Permissible variations with the outdoor climate are still larger in naturally ventilated buildings: $a = 0.255$ in de Dear and Brager (1998), 0.31 in ANSI/ASHRAE (2013), and 0.33 in (CEN, 2007). Particularly, the relationship found in ASHRAE RP884 (de Dear & Brager, 1998) for HVAC buildings predicts higher neutral temperatures than in the present study. This is likely explained by the inclusion of many buildings located in warmer climate regions in RP884's database. Previous studies have indicated that comfort temperature levels are not equal globally and that levels differ significantly among climate regions (Mishra & Ramgopal, 2013). This implies an important limitation of this study: some cultural variations may occur in different parts of the world due to different expectations and, therefore, extrapolation of the results to other climate regions should be done with care. Hence, the developed *T* limits are considered to be valid in temperate climate regions. Therefore, the comparison reveals that the developed limits differ substantially from those found in standards due to miscellaneous reasons, such as a higher activity level and different expectations compared with office environments, justifying the need for adaptive temperature limits specifically for the museum environment.

Another important aspect regarding perceived thermal comfort is clothing level. Figure 8 shows that clothing level depends on the outdoor temperature. The mean clothing levels range from 0.9 in winter to 0.4 in summer. Clothing differences among individual respondents were large. Some individuals practically wore summer outfits in winter, and others wore winter outfits in spring and summer. The clothing level of museum visitors provides a practical means to further adjust the indoor temperature while providing thermal comfort, *e.g.* by suggesting visitors wear their coat in winter and make use of the wardrobe in warmer conditions.

The results show significant differences in thermal sensation between individual visitors. Table 3 shows that women felt, on average, slightly, but significantly, cooler than men. Gender differences in thermal sensation have already been demonstrated in several studies (reviewed by Karjalainen, 2012) and may be even more prominent in museums with inhomogeneous indoor environments (Schellen et al., 2012), *e.g.* museums housed in historic buildings. This supports the finding that facilitating behavioural adjustments may further improve visitors' thermal comfort perception, *e.g.* by facilitating visitors to attune their clothing level to individual preferences.

More generally, indoor environments should provide thermal comfort to a building's occupants. Besides visitors, museum occupants include staff. This study, however, focused solely on the thermal comfort of museum visitors because staff consist of individuals working in the back office who are not exposed to conditions in the exhibition space, as well as security staff. The latter spend most of their time in the exhibition space, but, unlike visitors, do so every working day. Therefore, their physiological adaptation may be more prominent after longer periods of time working under varying indoor conditions. Moreover, behavioural adaptation may be easier, as staff members could easily alter their clothing in response to indoor conditions. For example, security staff may be provided with summer and winter outfits. More research is needed on the implications of the developed adaptive temperature limits for museum staff.

The developed temperature limits may be used to determine set-points for heating and cooling. However, besides thermal comfort, collection requirements determine *T* set-points. Therefore, a follow-up study (Kramer, van Schijndel, & Schellen, 2017) focused on developing a set-point algorithm to integrate collection and thermal comfort requirements. From a collection's standpoint, such an algorithm should include not only the absolute limits of the permissible temperature range, but also the permissible rate of changes per hour, day and season.

This study successfully applies the concept of adaptive comfort to a case study museum in Amsterdam, paving the way for improved energy efficiency and thermal comfort. Moreover, various directions for future research are identified. However, the results rely on one case study, and, hence, their extrapolation to other museums must be done cautiously by taking into account the following limitations: (1) some cultural variations may occur in different parts of the world due to different expectations; and (2) it will be important to validate these findings further in other buildings within the same climate and cultural context. Ultimately, the following can be concluded from the current study. An indoor temperature of 21°C without seasonal adjustments leads to discomfort in the case study museum. It is highly likely that this finding will also hold for other museums located in temperate climate regions with substantial seasonal variations, in warmer climate regions and in substantially colder climate regions. The mean clothing level can be viably predicted from the reference outdoor temperature, but differences among individuals are substantial. Clothing can be a practical means of further increasing the temperature range while maintaining (individual) comfort. Adaptive temperature limits have been developed according to the 90% acceptance class and are considered valid for temperate climates. The limits differ substantially from existing adaptive thermal comfort standards, justifying the need for adaptive temperature limits specifically for museums. Upper and lower temperature limits may be used to calculate heating and cooling set-points based on the reference outdoor temperature. The year-long measurement campaign in the case study museum demonstrated substantial energy savings (−49%) from the adaptive temperature limits in combination with ASHRAE class AA for RH control (45–55%).

Acknowledgements

The authors thank the Building Physics and Services Laboratory of Eindhoven University of Technology for its efforts regarding the experimental set-up. Moreover, they thank Antony Schellevis and Sebastiaan Lagendaal of Hermitage Amsterdam for their confidence and cooperation. The authors are grateful to Ms Marthe Doornbos, master's student, for extensive help with the thermal comfort surveys.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The Zeeuws Museum, Strukton Worksphere, Kuijpers Building Services, and Stichting PIT are greatly acknowledged for their financial support.

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