Building and Environment 175 (2020) 106779

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

The impact of a view from a window on thermal comfort, emotion, and cognitive performance

Won Hee Ko [a,*], Stefano Schiavon [a], Hui Zhang [a], Lindsay T. Graham [a], Gail Brager [a], Iris Mauss [b], Yu-Wen Lin [c]

[a] Center for the Built Environment, University of California, Berkeley, USA
[b] Department of Psychology, University of California, Berkeley, USA
[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, USA

ARTICLE INFO

Keywords:
Window
View
Thermal comfort
Emotion
Cognitive performance
Biophilic design

ABSTRACT

Visual connection to nature has been demonstrated to have a positive impact on attention restoration, stress reduction, and overall health and well-being. Inside buildings, windows are the primary means of providing a connection to the outdoors, and nature views even through a window may have similar effects on the occupants. Given that humans recognize environments through multi-sensory integration, a window view may also affect occupants' thermal perception. We assessed the influence of having a window with a view on thermal and emotional responses as well as on cognitive performance. We conducted a randomized crossover laboratory experiment with 86 participants, in spaces with and without windows. The chamber kept the air and window surface temperature at 28 °C, a slightly warm condition. The outcome measures consisted of subjective evaluations (e.g., thermal perception, emotion), skin temperature measurements and cognitive performance tests. In the space with versus without windows, the thermal sensation was significantly cooler (0.3 thermal sensation vote; equivalent to 0.74 °C lower), and 12% more participants were thermally comfortable. Positive emotions (e.g., happy, satisfied) were higher and negative emotions (e.g., sad, drowsy) were lower for the participants in the window versus the windowless condition. Working memory and the ability to concentrate were higher for participants in the space with versus without windows, but there were no significant differences in short-term memory, planning, and creativity performance. Considering the multiple effects of window access, providing a window with a view in a workplace is important for the comfort, emotion, and working memory and concentration of occupants.

1. Introduction

While early research and the current standards mostly focused on establishing the acceptable ranges of environmental conditions to reduce negative effects (e.g., discomfort or adverse health effects) [1–6], a new perspective on indoor environmental quality (IEQ) has gained traction in building research and practices in the past few years. With increasing attention in the building community being given to enhancing *positive impacts on occupants*, a growing body of research extends beyond the simple acceptability of indoor conditions to their influence on health, well-being, and productivity [7–9]. In order to promote the positive effects of the built environment, it is important to identify the most relevant parameters and attributes, while understanding the interactions and tradeoffs among IEQ factors. For example, one of the factors that provides a positive effect is a connection to nature. This concept is known as "biophilia" [10,11], and it is gaining prominence in the building industry [12–14].

In the built environment, providing a connection to nature positively impacts occupants' well-being [15,16] and satisfaction with a built space [17]. By reducing discomfort [18] and stress [19,20], biophilia thereby moderates the negative impact of job stress, which could otherwise lead to an increased probability of leaving one's job [21]. In buildings, windows are the primary means of providing this connection to the natural outdoors. Within areas near windows, occupants likely experience strong and varied sensory stimuli from the external environment. Vision is the primary sense that humans use to process their surroundings [22]. Given that humans recognize environments through multi-sensory integration [23,24], vision may have a relevant influence

* Corresponding author. 390 Wurster Hall, Berkeley, CA, 94720-1839, USA.
E-mail address: wonheeko@berkeley.edu (W.H. Ko).

https://doi.org/10.1016/j.buildenv.2020.106779
Received 20 December 2019; Received in revised form 10 February 2020; Accepted 1 March 2020
Available online 9 March 2020
0360-1323/

on how we perceive other senses. It may have psychological and physiological interactions with other sensory perceptions, such as thermal responses [25–27]. Hence, a window view may influence how we perceive different thermal environments in a given building. Visual and thermal comfort are subjective phenomena influenced by a range of factors that may differ when there are simultaneous inputs from other sensory systems (e.g., auditory, visual, tactile). Therefore, we must consider the possible interactions between visual and thermal perceptions. Ignoring the possible connections between these sensory systems could lead to ineffective design that could result in occupant discomfort or decreased performance, or even building performance issues such as energy waste.

While it is not known conclusively whether occupants' thermal responses differ when there is visual connection to the outdoors, there is some prior research that suggests this could be important. Some evidence shows that a visual connection to the outdoors can have a positive impact on the occupants' overall perceptions of the built environment, leading to flexibility in their expectations [28]. For instance, if we take this general concept and hypothesize that having a view to the outdoors could help occupants increase their satisfaction with a wider indoor temperature range, then we could relax the temperature setpoints, which would then allow a reduction in building energy consumption [29–32]. A reasonable amount of variability in the acceptable range may even be preferable for occupants [3,14]. For designers, it would be important to define the relevant parameters (i.e., view, daylight, and thermal conditions) and the interaction or tradeoffs between these parameters with regards to how they ultimately impact occupants' comfort, well-being and cognitive performance.

2. Problem statement

Previous studies investigated the impact of visual connection to nature on people, but it is rare to find studies that focus on the effects of a view from *a window* alongside consideration of the thermal environment. For example, most studies:

- use artificial visual stimuli (e.g., photos, images, and video clips) to represent the natural environment for an experiment [20,33–39] or;
- include outdoor activities rather than provide visual connection to nature within the built environment [40,41], or;
- do not control or monitor other environmental qualities (e.g., thermal) [16–18,42–45].

To consider the effects of a window view in building design and control, designers and engineers need quantifiable findings from well-controlled studies to explain the *sole* effects of a window and its view. In this regard, additional research is necessary to address the psychological and cognitive impacts of a view from a window on occupants and the subsequent tradeoffs with thermal comfort. The current research aims to address these considerations and explore:

- How do people's subjective appraisals of the thermal environment differ when they have visual connection to the outdoors through a window? Specifically, can occupants relax their expectations of the thermal environment or accept a wider temperature range (slightly warm or cool) when they have access to outdoor views?
- What are the emotional and cognitive effects of visual connection to the outdoors through a window? Can the view through a window improve psychological well-being and cognitive performance?

To overcome the research gaps and answer these questions, we assessed the influence of an outdoor view on occupants' thermal comfort, emotions, and cognitive performance through a laboratory study with human participants.

3. Method

3.1. Experimental design

We conducted a human subjects test using a randomized crossover study design. Each subject participated in two consecutive sessions with different environmental conditions: one with windows and one without. To avoid order effect, we counterbalanced the order and randomly assigned participants to their order (first window then windowless, or first windowless then window; 43 participants in each condition). Participants completed the same measures (see Section 3.5), in the same sequence for both conditions (Fig. 1-D). The experiments took place between September to October 2018.

3.2. Participants

A total of 86 participants (43 males and 43 females) took part in the experiments. We recruited participants through posted flyers and email invitations, representing a sample of undergraduate and graduate students from the University of California, Berkeley. The pre-selection process was based on the following criteria: participants needed to be at least 18 years of age, have no vision impairments (e.g., color blindness, eye disorders), no sleep disorders, and no medications or night shifts that might influence their sleep patterns. The Committee for the Protection of Human Subjects at the University of Berkeley has reviewed and approved the study protocol (2018-06-11172). All participants provided informed consent, and each participant was compensated $45 for a 1-h orientation and 2-h experimental session.

3.3. Test room set-up and equipment

We conducted the study in the Controlled Environmental Chamber at the University of California, Berkeley, an office-like test room, which measures 5.5 m × 5.5 m x 2.5 m (Fig. 1-A and 1-C; [46,47]). The chamber has overhead lighting (5000 K) and the air handling system maintains desired air conditions in the main chamber. The plenum-wall facing the exterior allows a continuous stream of temperature-controlled air to pass between the inner (single-pane) and outer (double-pane) glazing of the windows (2.2 m × 1.5 m, 48% Window-to-Wall Ratio). It controls the surface temperature of the windows, and the exterior wall surface temperature around the windows. The windows are shaded by large overhangs and trees in front, allowing only diffused daylight (~150 lux; horizontal illuminance at the desk level) to enter the space (Fig. 1-B). In order to create the two conditions (one with a window and one without), we placed a floor to ceiling curtain in the middle of the chamber. Both spaces were the same target temperature, 28 °C, a slightly warm conditions based on ASHRAE Standard 55's thermal comfort range [2,48]. Additionally, we monitored the physical environmental conditions (i.e., air temperature, air speed, relative humidity, radiant temperature, light level, and CO_2 level) and outdoor conditions (i.e., solar radiation and air temperature obtained from the weather station at the Lawrence Berkeley National Lab [49]). Appendix A summarizes the device and measurement uncertainty.

3.4. Procedure

3.4.1. The preparation for the main session

Before the day of the experiment, we offered an orientation session for participants. The goal of the orientation was to outline the experiment and to have participants practice the cognitive performance tests in order to minimize the learning effects (i.e., increase in a participant's test score from one administration to the next). Next, we invited four participants to the main experiment at a time according to their availability. During the experiment, they were required to wear a long-sleeve shirt, trousers, and closed-toe shoes with socks to reflect a 0.7 clothing insulation value [2]. The experiment lasted 2 h (either 10 a.m. to 12 p.

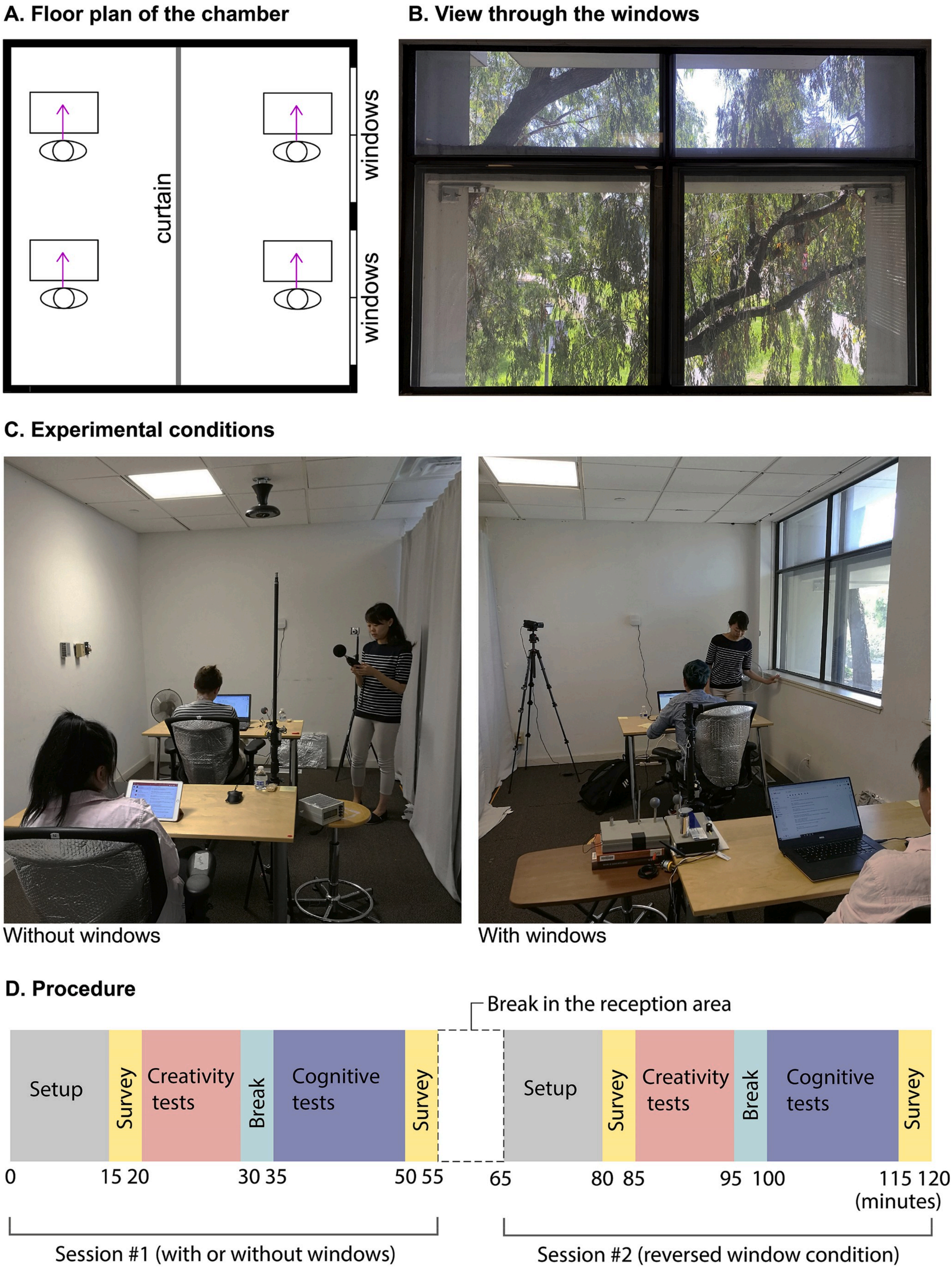


Fig. 1. A. Graphical floor plan of the climatic chamber; B. View through the windows; C. Experimental conditions: the space without windows (L) and the space with windows (R); D. Experimental procedure.

m., or 2 p.m. to 4 p.m.) and consisted of two consecutive sessions of 55 min each, including a 10-min break in the reception area. The structure of the two sessions was identical except for the environmental manipulation (i.e., with windows or without).

3.4.2. The main session procedure

Fig. 1-D describes the procedures of the experiment. On the experiment day, we randomly assigned four participants to the initial condition they would experience: two participants at the space with windows and the other two at the space without windows. After the first session, they switched to the reversed window condition for the second session. There was no odd number but we dropped the data from two participants who violated rules of experiments (e.g., drinking iced water in one of the sessions). Once they settled at the designated workstation, we helped them to attach skin temperature sensors (iButton; DS1921H-F5, Maxim Integrated, USA) at four body locations (back of the neck, right scapula, left hand, and right shin) following ISO 9886 [50]. We gave participants an initial survey that included questions about their thermal perceptions of the space, emotion, perceived stress level. Next, participants completed a creativity performance test. Following the creativity tests, we gave participants a 5-min break at their assigned workstation. During the break, we asked them not to use any electronic devices (e.g., laptops or mobile phones). We deliberately assigned the brief break to allow participants the potential to recover their attentional capacity before the cognitive performance tests, recognizing that this effect might differ in the spaces with and without windows. According to the Attention Restoration Theory [51], engaging with nature effortlessly allows people to recover the ability of directed-attention. As it is a single-blind study where the participants do not know the main objectives and hypotheses of the study, we did not force them to look out of the window during the break if they were in that space. Rather, we hoped that by asking them not to use any electronic devices, it would naturally motivate those who had windows to look outside, as they did not have much else to do during the break. After the break, they performed the cognitive tests and completed a final survey, which was same as the initial survey including an additional survey on eye symptoms. After the survey, participants took a 10-min break in the reception area. After this second, longer break, they repeated the same procedure in the reversed window condition.

3.5. Measures

3.5.1. Thermal perceptions

We measured subjective thermal perceptions of participants with a survey questionnaire aimed at measuring in-the-moment thermal sensation, comfort, acceptability, and pleasure. The participants answered questions about their thermal sensation using the ASHRAE seven-point continuous scale from "cold" to "hot." Both thermal comfort and acceptability scales also used a seven-point continuous scale from "very uncomfortable" or "very unacceptable" to "very comfortable" or "very acceptable" with an exclusion of the non-zero value as there is no neutral value for comfort or acceptability. The thermal pleasure scales ranged from "very unpleasant" to "very pleasant" [52,53]. Here, we only report the data from the final thermal comfort survey given because we are interested mainly in steady-state conditions. We also collected the skin temperature for four body parts of each participant and calculated the mean skin temperature (t_{sk}) under the warm condition based on the following equation from ISO 9886 [50]:

$$t_{sk} = 0.28t_{neck} + 0.28t_{scapula} + 0.16t_{left\ hand} + 0.28t_{shin} \quad (1)$$

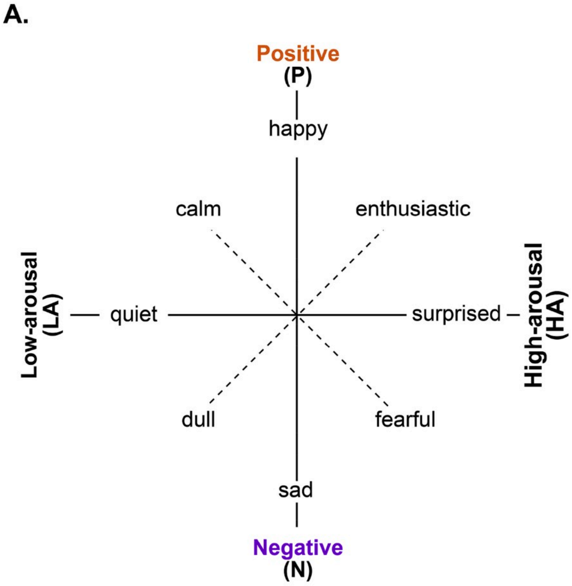
3.5.2. Emotion

To comprehensively assess the emotional state of the participants, we used the circumplex model [54,55]. Fig. 2-A describes the model which yields eight emotion categories and Fig. 2-B shows the items for each octant. Specifically, the model posits a structure of emotion in which four poles (on an x–y axis) represent different emotional states, from low-arousal to high-arousal, and from negative to positive emotion. Some studies in landscape [56,57] and lighting [58] used the model to measure emotional states, and it is also one of the most widely used and validated measure in psychological research of emotion [59]. Our survey questionnaire asked participants "To what extent do you feel this way right now, that is, at the present moment?" by using a Likert scale ranging from "1" (not at all) to "5" (extremely). The acronyms in Fig. 2-B will be used when discussing results.

3.5.3. Cognitive performance

To assess the impact of a window view on cognitive performance of the occupants, we used four modules of Cambridge Brain Sciences, a web-based platform for the assessment of cognitive function [60]. The modules used were Token Search (working-memory), Double Trouble

A.



B.

Octant	Item
High-arousal positive (HAP)	enthusiastic, excited, elated
Positive (P)	happy, satisfied, content
Low-arousal positive (LAP)	calm, relaxed, peaceful
Low-arousal (LA)	quiet, still, passive
Low-arousal negative	dull, sleepy, drowsy
Negative (N)	sad, lonely, unhappy
High-arousal negative	fearful, hostile, nervous
High-arousal (HA)	surprised, aroused, astonished

Fig. 2. The affective circumplex: emotion octant and items [55].

(concentration), Digit Span (short-term memory), and Spatial Planning (planning). Appendix B describes each test in detail. Their selection was based on the Attention Restoration Theory [51] and related studies [41, 61,62], which have shown that the participants' experience with nature improved their concentration, short-term or working memories. We also included the planning task that requires executive function (e.g., brain-reasoning and forward-thinking), which knowledge workers would need to perform their task successfully [63]. The cognitive performance tests took approximately 15 min to complete. The participants who finished the tests earlier than others took rest at their workstation while waiting for everyone in the session to complete.

In addition to the Cambridge Brain Sciences' four modules, we administered a creativity performance test. To do so, we adapted the Alternative Uses Task (AUT) that evaluates the creativity construct of divergent thinking [64]. Creativity is an essential psychological ability that both organizations and individual workers need to perform their knowledge-based tasks successfully. The AUT is the commonly used creativity test in both building science and environmental psychology research [65–69]. As an example of previous findings, these studies found an enhanced ability to think of alternative uses for a common object under the experimental conditions with more environmental stimuli or more spacious scenery. The creativity performance tests took 10 min to complete.

3.5.4. Eye symptoms and perceived stress level

As contemporary office tasks have become increasingly computer-based, 90% of computer workers experience Computer Vision Syndrome due to performing a sustained near-vision task [70]. Windows in the office environment may provide an opportunity for occupants to look away from electronic screens, thus relieving eye muscle fatigue [71, 72]. To assess the window effect, we asked participants to complete a questionnaire asking about their level of ocular discomfort in the final survey that was administered in each experimental condition. This questionnaire [70] asks participants to rate ten elements related to multiple ocular symptoms (e.g., dry eye, blurred vision) by using a five-point Likert scale ranging from "1" (not at all) to "5" (extremely).

In addition to the eye symptom measures, we also included perceived stress level ratings, the common items on questionnaires in environmental psychology that investigates the effect of exposure to natural environment [35,38]. We asked participants to rate their perceived stress level at the moment using a five-point Likert scale ranging from "1" (not at all) to "5" (extremely).

3.5.5. Potential moderator variables

Individual differences (e.g., body mass index (BMI), sex) and contextual factors (e.g., time of day, illuminance level) may affect occupants' environmental responses. The effects of these factors in indoor environmental quality research have been extensively studied [73–75], yet in previous studies, these variables have not been commonly controlled or measured. As the present study includes various psychological and cognitive outcome measures, we tried to collect any personal and contextual factors that may influence the results. Table 1 summarizes these factors.

Table 1
Potential factors may moderate the effect of the experimental conditions (i.e., with or without windows) on the outcome measures.

Factor	Balanced Factor	Observed Factor	Outcome variables
Order of the experimental conditions	X		ALL
Sex	X		ALL
Horizontal Illuminance at desk		X	ALL
Outdoor solar radiation level		X	ALL
Time of the day		X	Emotion
Body Mass Index (BMI)		X	Thermal perceptions

We considered sex and order of the experimental conditions (first window then windowless, or first windowless then window), but balanced them across conditions. Previous studies found that perceptions of the environment and related psychological impacts differ across females and males. This has been found in studies of thermal comfort [76–78], visual perception [79,80], and cognitive performance [81,82]. Order effect has also been a potential moderating factor in similar experimental designs [27,61]. By randomizing and counterbalancing sex and order of the experimental conditions, we distributed these effects evenly across the experimental conditions so they did not confound the outcomes of interest for each experimental condition.

We also collected participants' BMI, a measure of body fat based on a person's weight and height, as previous studies demonstrate that it is correlated to the thermal response of individuals [83]. We also recorded the "time of the day" the experiment took place, as it may influence on emotional response [84]. We were not able to balance it across the experiment due to the conditions of the climatic chamber and to participants' availability (47% of the experiments were in the morning and 53% in the afternoon). Indoor horizontal illuminance level at the desk and outdoor solar radiation level are also considered as potential moderating factors as they changed slightly across conditions due to weather conditions.

3.6. Statistical analysis

We tested the effects of the experimental conditions (i.e., with or without windows) on the outcome measures (e.g., thermal perceptions, emotion and cognitive performance) with permutation tests. Permutation tests are non-parametric tests that do not rely on a model (i.e., parametric assumptions and given distribution) [85]. The permutations randomly switch (with probability 0.5) the window and windowless label within each participant, and then we look at the mean difference between the window and windowless condition for each permutation. The *p*-value is the number of the *permutation* mean differences that are larger than the *observed* mean difference. For the permutation tests, we used the Asymptotic General Symmetry Test that paired results from the same individual with and without the window condition (i.e., repeated measure) and then analyzed the difference between the conditions for each individual. To assess if the potential moderator variables (Section 3.5.5) influenced the effect of the window vs. windowless experimental conditions, we used the Asymptotic General Independence Test, which treats the moderator variable groups (e.g., male versus female) as independent samples, and tests if there is a difference in the effect of the experimental conditions between the moderator variable groups. After we calculated the *p*-values from the permutation tests, we applied the Bonferroni correction factors to the critical alpha levels of each outcome family to control the familywise error rate. The family Bonferroni correction reduces type I error (risk of finding spurious effect) but it increases type II error (risk of missing real effect). We used this conservative approach to increase the confidence of the discovered effects, by dividing the critical *p*-value for significance (0.05) by the number of tests in each family of the outcome measures. For example, we set the critical alpha value as 0.0125 (0.05/4) for the thermal perception questions as it has four tests. For the emotion questions, we set the critical alpha value as 0.00625 (0.05/8) as it has eight tests. We did not apply the correction factor to the cognitive performance results as each test is independent of each other, and the selection of each test was based on the previous literature that supports the significant effects of nature on the five cognitive functions. In addition, we did not find any strong reason to avoid type I error as having a window in a space may not cause any serious negative impact on the cognitive function of the occupants. To test effect sizes, we reported r values [86]. According to previous literature, we can interpret effect size using the thresholds for a recommended negligible (<0.2), small (0.2–0.5), moderate (0.5–0.8), and large effect (>0.80) [87]. There are some debates related to the thresholds which we will discuss in Section 5.5. We used the statistical software R [88] and the R package "coin" [89] to perform the permutation tests.

4. Results

4.1. Environmental conditions

We monitored IEQ physical factors (i.e., thermal, lighting, and air quality) to ensure that the environmental conditions of the two spaces (i.e., with and without windows) were considered to be identical. We measured the operative temperature at three levels (0.1, 0.6, and 1.1 m) of each space, and calculated the numerical average, which represents the thermal condition of seated occupants [2]. The average operative temperatures were the same (M_{window} = 28.0 °C, SD_{window} = 0.2 °C; $M_{windowless}$ = 28.0 °C, $SD_{windowless}$ = 0.1 °C). The difference between the two spaces per session was less than 0.3 °C ($M_{windowless\text{-}window}$ = - 0.0 °C, $SD_{windowless\text{-}window}$ = 0.1 °C). We also measured horizontal illuminance levels at the desk (i.e., task plane, 0.73 m from the floor) to assess the lighting condition of each space over the experiments [90]. While the windowless condition had continuous illuminance level (M = 450 lux, SD = 0.1 lux), the illuminance level of the window condition changed slightly across experiments (M = 461 lux, SD = 39.5 lux). It was due to the temporal effect of diffused daylight each day, but the values did not vary much across the experiments and were within the recommended indoor lighting level [90]. The sky conditions during the experiments were mostly clear and sunny (outdoor solar radiation; M = 541 W/m^2, SD = 120 W/m^2). The prevailing mean outdoor temperatures ranged from 14 °C to 17 °C (M = 15.7 °C, SD = 0.8 °C). The other measured thermal (i.e., relative humidity, air speed) and air quality (i.e., CO_2 level) factors did not vary significantly across the experiments and were within allowable ranges for indoor environments [1,2]. Appendix A summarizes the measured values.

4.2. Thermal perceptions

At the slightly warm ambient condition (28 °C), the participants reported feeling slightly cooler in the window condition compared to when they were in the windowless condition (Fig. 3-A). Participants' mean thermal sensation vote (TSV) was 0.3 lower in the window condition (Z = - 2.72, p = 0.006, r = 0.29). Further, 12% more participants were thermally comfortable in the window condition (Z = 2.99, p = 0.003, r = 0.32; Fig. 3-B). 7% more of participants felt that the thermal environment in the window condition was pleasant (Z = 2.95, p = 0.003, r = 0.32; Fig. 3-D) even though the thermal environment of the two spaces were identical (See Appendix C for additional graphs). After the Bonferroni correction (p < 0.0125; 0.05/4), the results of thermal acceptability of participants were not statistically different. We found that 5% more participants, a relatively small number, reported acceptance of the thermal environment of the window condition compared to that of the windowless condition (Z = 2.33, p = 0.02, r = 0.25; Fig. 3-C). The results of participants' mean skin temperature measurements showed no statistically significant differences (Z = 1.69, p = 0.09, r = 0.18) between the window condition (M = 33.76, SD = 2.47) and the windowless one (M = 33.78, SD = 2.48), thus indicating that the physiological conditions influenced by the thermal conditions of the two spaces were not significantly different.

4.3. Emotion

Overall, participants reported LAP emotion during the experiment such that LAP emotion ratings were higher than all other emotions (Fig. 3-E). When comparing the window to the windowless condition, as indicated in Table 2, participants reported small but statistically significant (p < 0.00625; 0.05/8), higher positive emotions (P) and lower negative emotions (LAN and N). The window condition did not have a significant main effect on HAP, LAP, HAN, HA or LA.

4.4. Cognitive performance

Participants performed better on two (i.e., working memory and concentration) of the four Cambridge Brain Sciences' modules given when they were in the window condition. The scores of the other two tests (i.e., short-term memory and planning), and the creativity test (i.e., divergent thinking test), did not show any significant differences between the two experimental conditions. Fig. 4-A summarizes the mean percentage improvements in the cognitive performance scores by having a window.

The participants' score of working memory tests were 6% higher in the window condition ($Median$ = 10, MAD = 3.00) compared to the windowless one ($Median$ = 9, MAD = 1.48) at the 0.009 level of significance (Z = 2.60, p < 0.01, r = 0.31). The participants' score of concentration tests were 5% higher in the window condition ($Median$ = 52, MAD = 10.38) compared to the windowless one ($Median$ = 49, MAD = 11.86) at the 0.03 level of significance (Z = 2.18, p = 0.03, r = 0.26). The scores for the short-term memory (Z = 0.31, p = 0.75, r = 0.04) and planning tests (Z = - 0.63, p = 0.53, r = 0.08) were not significantly different between the two window conditions.

The results from the divergent thinking test did not show a significant difference between the two window conditions (Z = 0.07, p = 0.94, r = 0.01). Results indicate that there was no main effect of window condition on the ability of divergent thinking of participants.

4.5. Eye symptoms and perceived stress level

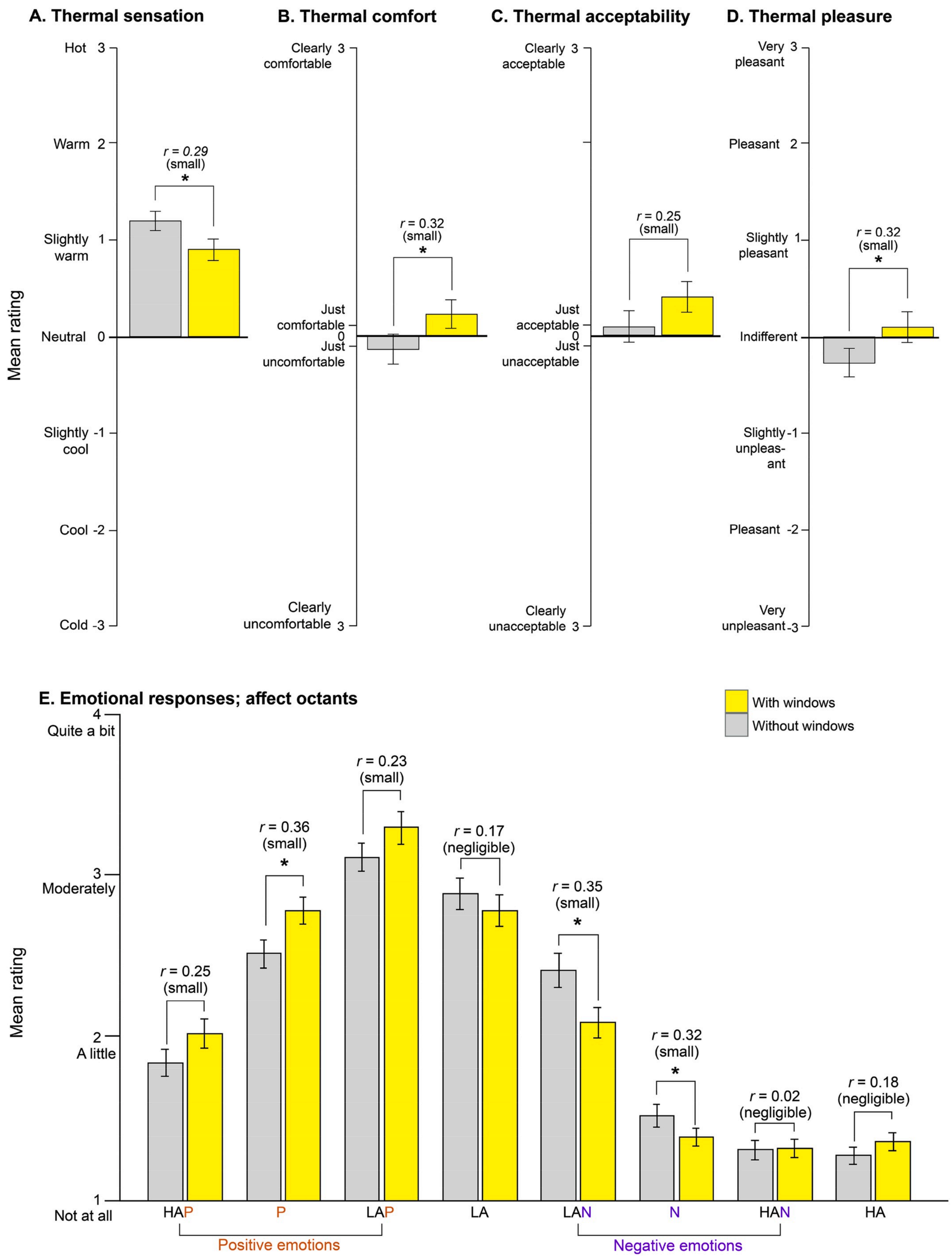
Participants reported experiencing less ocular symptoms (e.g., dry eye, blurred vision) in the condition with the window compared to the windowless one (Fig. 4-B). The mean eye symptom scores of the window condition (M = 2.2, SD = 0.71) were 10% lower compared to the windowless one (M = 2.42, SD = 0.77) at the 0.002 level of significance (Z = −3.08, p < 0.01, r = 0.33). Fig. 4-B describes the mean of perceived stress level with the standard error mean bars in the final survey. The reports from participants regarding perceived stress level did not show a significant difference between window conditions (Z = 1.34, p > 0.05, r = 0.14).

4.6. Potential moderator variables

To understand the contribution of potential moderator variables (i.e., individual differences and contextual conditions) on the effect of the experimental conditions (i.e., with or without windows), we conducted permutation tests using the Asymptotic General Independence Test. We analyzed the effect of the order of the experimental conditions (first window then windowless, or first windowless then window), time of day, horizontal illuminance level at the desk, outdoor solar radiation level, and participants' sex and BMI on the window effects. We also applied the Bonferroni correction factor when analyzing the moderator variables on each outcome family (i.e., p < 0.0125 for thermal perception and p < 0.00625 for emotion). For brevity, we only summarize significant moderator variables in the following paragraphs.

BMI moderated the effects of the experimental conditions on thermal pleasure. In comparing the window to windowless condition (Z = 2.67, p = 0.008, r = 0.29), the overweight participants (i.e., BMI > 25) reported that the thermal environment in the window condition is more pleasant ($M_{difference}$ = 1.12) than the under-weight or normal-weight participants ($M_{difference}$ = 0.23). The moderator variables did not, however, influence the window effects on the other thermal perception metrics (i.e., thermal sensation, thermal comfort, and thermal acceptability) or on emotion.

The order of the experimental conditions did not moderate the effect



(caption on next page)

Fig. 3. Mean of the thermal perceptions (A. to D.) and the emotion ratings (E.) with the standard error mean bars in the final surveys; Bonferroni-corrected significance levels: *p < 0.0125 (0.05/4) for the thermal perception results, *p < 0.00625 (0.05/8) for the emotion results; effect size (r): negligible (<0.2), small (0.2–0.5), moderate (0.5–0.8), and large (>0.80). A. Thermal sensation; B. Thermal comfort; C. Thermal acceptability; D. Thermal pleasure; E. Emotion octants with sampled items: HAP = high-arousal positive; P = positive; LAP = low-arousal positive; LA = low-arousal; LAN = low-arousal negative; N = negative; HAN = high-arousal negative; HA = high-arousal.

of the experimental conditions on thermal perceptions, emotion and cognitive performance but we found the order effect on the results of eye symptoms and perceived stress level. In comparing the window to the windowless condition ($Z = -2.85$, $p = 0.004$, $r = 0.31$), the participants who had the windowless condition first reported experiencing much fewer eye symptoms in the window condition ($M_{difference} = 0.40$) than the participants who had the window condition first ($M_{difference} = 0.03$). Similarly, in comparing the window to windowless condition ($Z = -2.76$, $p = 0.006$, $r = 0.30$), the participants who had the windowless condition first reported experiencing a higher perceived level of stress in the window condition ($M_{difference} = 0.33$) compared to the participants who had the window condition first ($M = 0.11$). These indicate that each participants' experience in the first session may have influenced the result of eye symptoms and perceived stress level in the second session. In addition, we found there were learning effects (i.e., increase in a participant's test score from one administration to the next) in the results of the concentration test ($Z = 2.07$, $p = 0.04$, $r = 0.25$) and the planning test ($Z = 2.54$, $p = 0.01$, $r = 0.31$). This indicates that the two practice rounds of the cognitive performance tasks did not fully help the participants overcome the learning effect in the two tasks. Although these findings do not affect the validity of the main results of the study, because the order of the experimental conditions and the session number was counterbalanced and randomized, they have important implications for the experimental design of future studies investigating eye symptoms, perceived stress level, and some cognitive performance (i.e., concentration and planning performance) through within-subject experiment design (i.e., repeated measure).

Table 2
Effect of being in the space with windows versus without on emotion: Z-statistics, statistical significance (p-value; permutation test), and effect size (r).

Octant	Z	*p*-value	Effect size (*r*)
High-arousal positive (HAP)	2.32	0.02	0.25 (small)
Positive (P)	3.37	0.0007 *	0.36 (small)
Low-arousal positive (LAP)	2.17	0.03	0.23 (small)
Low-arousal (LA)	−1.57	0.12	0.17 (negligible)
Low-arousal negative (LAN)	−3.27	0.001 *	0.35 (small)
Negative (N)	−3.01	0.003 *	0.32 (small)
High-arousal negative (HAN)	0.17	0.86	0.02 (negligible)
High-arousal (HA)	1.70	0.09	0.18 (negligible)

*Note. * Statistical significance after the Bonferroni correction (p < 0.00625; 0.05/8).*

5. Discussion

5.1. Effects of the outdoor view from the window on thermal perceptions

The findings from the study indicated that in a slightly warm environment (28 °C), participants with a visual connection to the outdoors through a window felt cooler (with a mean difference of 0.3 in the TSV), more comfortable and pleasant (with a mean difference of 0.4 in the thermal comfort and thermal pleasure ratings) compared to those without a window. This finding suggests that people close to windows are more forgiving of small thermal comfort deviations, which could imply that one could slightly relax the constraints of thermal comfort for the area closest to the perimeter. We calculated the equivalent temperature difference of the 0.3 TSV based on the Griffith method that uses

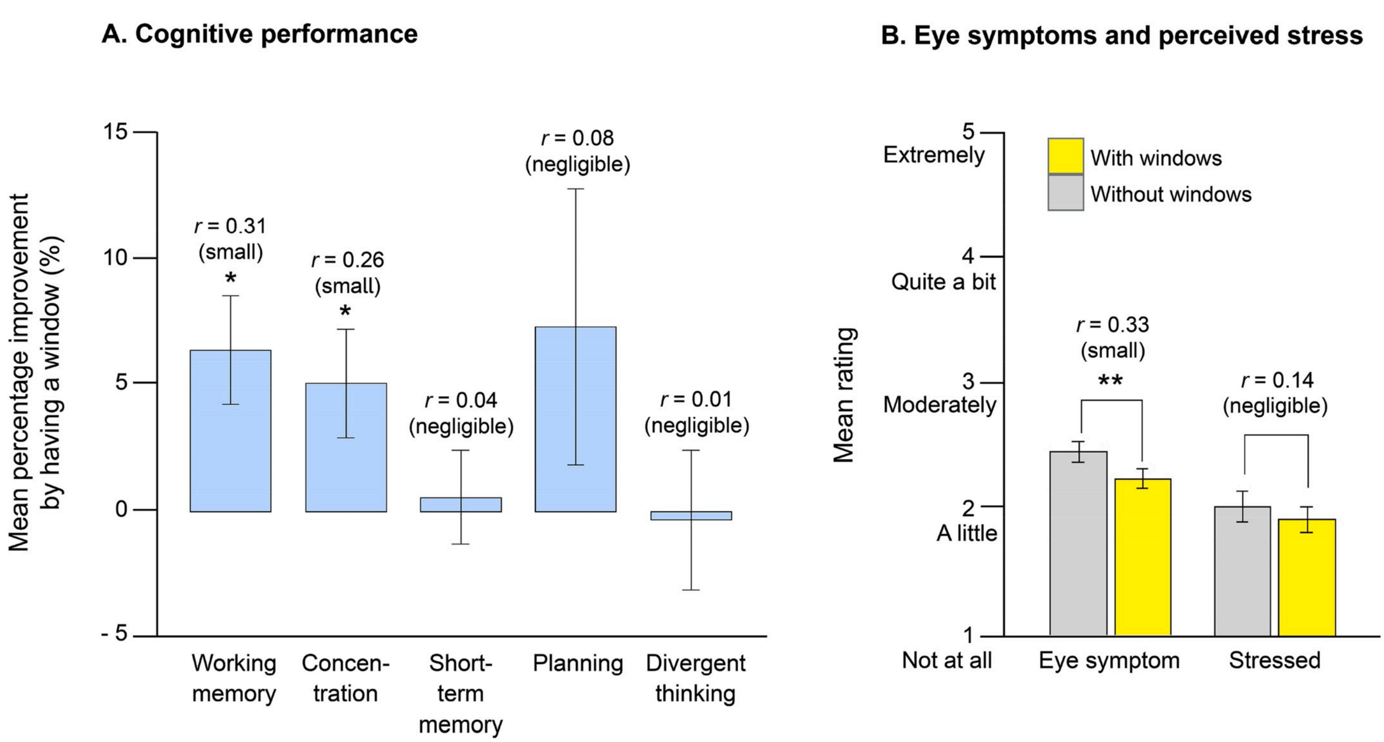


Fig. 4. A. Mean of the percentage improvements by having a window in the cognitive performance tests with the standard error mean bars; B. Mean of the eye symptom scores and perceived stress level with the standard error mean bars in the final surveys; statistical significance: *p < 0.05, **p < 0.01, ***p < 0.001; effect size (r): negligible (<0.2), small (0.2–0.5), moderate (0.5–0.8), and large (>0.80).

0.4/K as a regression gradient [91,92], equivalent to an interval of 2.5K between the TSV scale. Based on the calculation, we could interpret our findings (0.3 TSV difference) that having a window has an equivalent 0.74 °C (1.33 °F) cooling effect on the participants.

To understand the energy saving potential of increasing the cooling setpoints by 0.74 °C, we refer to two studies exploring the energy saving benefits of extending air temperature setpoints [29,93]. Based on simulated results (varying the temperature setpoints to yield the average heating, ventilation, and air conditioning (HVAC) energy saving potentials), increasing the cooling setpoint by 0.74 °C can achieve an average savings of approximately 8% in cooling energy and 6.5% of total HVAC energy for a medium-sized office building in San Francisco, and 6% of total mechanical system energy saving in typical Singapore buildings. Even though the values would differ depending on the climate, building layout and the HVAC system types, it roughly shows the potential energy benefits of lowering the TSV by providing visual connection to the outdoors through windows.

We still do not have a full explanation for why participants felt cooler and more comfortable in a space with windows, however, we think three aspects may explain our findings:

- **A window as a source of distraction.** Some of the participants said that the window helped them shift their focus from their thermal discomfort to the much richer sensory stimuli seen through the window (i.e., an outdoors view, including trees). Therefore, having stimuli to shift the attention of an occupant from discomfort could increase overall thermal comfort.
- **Psychological adaptation.** By looking out the window, people understand that the external environment is sunny and warm, so this might be associated with an expectation of the indoor temperature being warmer as well. In other words, altered perception of and reaction to sensory information because of past experience and expectations [94] can increase one's ability to "forgive" environmental conditions that in other cases may be deemed unacceptable [28]. This psychological dimension of thermal adaptation is also a key factor of the adaptive thermal comfort model [3].
- **Compensation effect of indoor environmental factors.** Some researchers have found that indoor environmental factors may compensate for one another [95,96]. For instance, a high-quality factor (i.e., having a window) can compensate for the possible negative effect of a low-quality factor (e.g., an unpleasant thermal environment) to a certain extent.

5.2. Effects of the outdoor view from the window on occupant emotions

Participants' self-reports of emotion seen in both the initial survey and the final survey indicated that the positive effect of having exposure to windows was instantaneous and also remained constant throughout the hour-long study. We do not know how long this positive effect would last in practice. Some field studies have found increased satisfaction with the workplace when occupants have a window in their space [97], have the better access to windows [98,99], or are satisfied with their external view [100]. However, these findings are often insufficient to generalize about any long-term effects of windows as they did not: 1) control other environmental qualities or contextual factors (e.g., time of day); or 2) have a sample size that can represent the general population [101].

In the current study, the general pattern of results showed that positive emotion (P) was higher, and negative and low-arousal negative emotions (N and LAN) were lower for participants in the window condition compared to the windowless one. Different from the results of other negative emotions, participants' levels of high-arousal negative emotion (HAN; e.g., angry) were not significantly impacted by the window condition. It may be because participants did not have a high enough level of high-arousal negative emotion (i.e., $M_{window} = 1.28$, $SD_{window} = 0.48$; $M_{windowless} = 1.33$, $SD_{windowless} = 0.48$) to see an effect of having a window.

5.3. Effects of the outdoor view from the window on cognitive performance

Among the four cognitive performance tests that the participants completed, the results showed only a statistically significant difference in working memory and concentration tests when participants were in the window versus the windowless condition. These results are similar to previous studies and the theory of the restorative effects of nature [40,43,62], which shows an improvement in working memory and concentration when occupants experience a connection with nature. The results of the current study show that visual connection to nature even through a *window* (and only 55 min exposure) can provide results that are congruent with showing a video or photos of natural scenes [33,39], or even more immersive experience with nature, such as a back-packing trip or walking in the forest [40,41].

However, it should be noted that the current study did not find any effect on short-term memory or planning ability. This partially contradicts findings from previous studies [98]. It may be due to the slight thermal discomfort setting of the current. Some studies found that moderately higher temperatures incurred significantly reduced cognitive performance [103]. However, the effect of moderate heat stress on cognitive performance is still controversial [104]. Therefore, we cannot conclude that the visual connection through a window has a positive impact on the various cognitive abilities of the occupants of the space, but it does enhance the working memory and concentration.

5.4. Effects of the outdoor view from the window on perceived stress level

Perceived stress level were also not significantly different between the two conditions, in contrast to the Stress-reduction theory [20,36,105], which suggests that humans can reduce stress by viewing a nature scene. This may be due to the activities (i.e., surveys, cognitive performance tests) that we provided in the study, which may not have induced a high enough level of stress to see a change. Further, the short-term exposure to the window condition may have limited the ability to observe subtle shifts in stress levels.

5.5. Study limitations

One of the limitations of the current study is the potential contribution of non-visual effects from daylight on the outcome variables. Due to the nature of windows, which transmit both daylight and a view to the outdoors, we were not able to completely control the transmission of daylight in the window condition and therefore separate these effects entirely. This is a confounding factor also present in studies looking at the effect of daylight on people [27]. We instead allowed relatively small daylight effects (~150 lux, roughly 30% of the total illuminance level at desk) from the windows while keeping a very similar level of horizontal illuminance between the two conditions. In order to understand if non-visual effects of daylight contributed to the findings, another study should be done. The new study could compare the results from 1) a space with diffused daylight through a translucent window or a skylight (no visual connection to the outdoors) and a space with windows or 2) a windowless condition with a circadian lighting panel (which produces a similar color temperature and spectral distribution as sunlight) and a space with windows. Analyzing the non-visual effects was not the main focus of this set of experiments, so we reserved the idea for further study.

We assessed the effect of a window view in a slightly warm condition (28 °C) only. Even though our findings provide relevant insights into buildings in warm areas, our findings do not provide a full picture of how having a window would impact the thermal perceptions in other conditions. In order to fully understand the window effect on thermal responses, we should conduct several more lab studies that include slightly cooler conditions as well as more gradual temperatures for slightly warm conditions (e.g., 26 °C, 27 °C, etc.) to determine if the window effect remains the same magnitude.

Our findings are based on the windows of the chamber that provided a natural view that consists of mostly trees that were very close to the window and a sunny sky in the Bay Area. If the window view had different contents (e.g., buildings and an overcast sky) and luminance patterns, the effects of the window could be either decreased or increased. Some studies found that people preferred natural, dynamic, but distant views compared to human-made, still, close views [106–108]. Future studies are necessary to assess the acceptable or minimum quality of the window view content that would cause the "window effect" and its magnitude.

The current study tested a very short-term exposure (55 min) to the different window conditions in the lab study settings due to the limitations of time and budget. The major findings of the study demonstrate that a short exposure to the window has positive effects on the thermal, emotional, and cognitive perceptions of the occupants. However, in order to investigate the prolonged effects of a visual connection to the outdoors, which is more relevant to the everyday exposure of office workers, a longitudinal study at a field site would provide more detailed results that could more clearly support changes in office building design and control.

Lastly, the effects of a window in the study were all small (ranging from 0.29 to 0.36) based on Ferguson's thresholds for effect size [87], which is a conservative value compared to Cohen's thresholds for effect size [86]. This may bring up a concern about the practical utility of the reported effect sizes. However, the use of thresholds for effect size is still controversial. Some researchers demonstrated that Cohen's thresholds were too low, which produced inflated effects in the study findings [87]. On the other hand, others argue that Cohen's thresholds are too conservative and sometimes underestimate the potential of the effects in social science research [109]. Before evaluating the effect sizes, we should also consider the intent of the study and how extreme or artificial effects were tested in psychological research. The current study was designed to detect the effects of having a visual connection to nature through a window without exposing the participants to extreme or unnatural conditions, so that the conditions would be closer to the subtle differences that people find in their everyday life in the built environment. In this regard, the statistically significant but small effect size still provides meaningful knowledge relevant to the building industry. In addition, the results demonstrated a positive impact on multiple aspects (thermal comfort, emotion, cognitive performance, and eyestrain) for the occupants. Hence, considering that the effect size in isolation may not be relevant for indoor environmental quality research, it often interacts with and compensates for multiple different psychological factors.

6. Conclusions

This study investigated the thermal perception and emotional and cognitive impacts of having a view to the outdoors via a window in a working environment. To our knowledge, it was the first to investigate the main effect of an outdoor view from a window on thermal perceptions. We also examined the effect of having a window on occupant emotions and cognitive performance, which previous studies have not studied in a controlled experimental environment. Across all the areas that we examined (i.e., thermal perceptions, emotion, and cognitive performance), our findings consistently show statistically significant, but practically small, improvements in these variables by providing occupants with a visual connection to the outdoors through a window in a short period time (55 min). However, results showed that windows with a view did not have an effect on short-term memory, planning, or divergent thinking in the settings we studied.

The findings have three important implications: 1) they demonstrate that people close to a window may be more forgiving of small thermal comfort deviations, which can result in potential energy savings through setpoint adjustments; 2) having a window enhances psychological well-being by enhancing positive emotion and reducing negative emotions; and 3) providing visual connection to the outdoors supports working-memory and concentration that may be directly related to a worker's productivity. Considering the multiple effects of window access, we see that providing a window in a workplace is important for the comfort, well-being, and productivity of occupants. A novel finding of the study shows that a positive effect on thermal perceptions may be at play when windows are present and could provide an effective design solution that enhances the comfort of the occupants, while saving energy in the built environment, especially for cooling-dominated climates.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was mainly supported by the Center for the Built Environment (CBE), at the University of California, Berkeley. This research was also partially supported by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. The authors would like to thank Lisa Heschong for her advice and support on the experimental design. We also would like to thank Amanda Glazer, Jake Spertus (The Department of Statistics, at the University of California, Berkeley) and Michael G. Kent (BEARS) for their advice on the statistical analysis. We sincerely appreciate the 86 subjects who participated in this study.

Appendix A

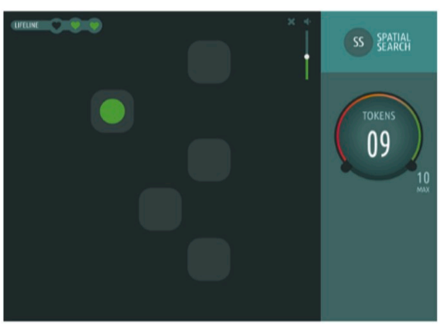
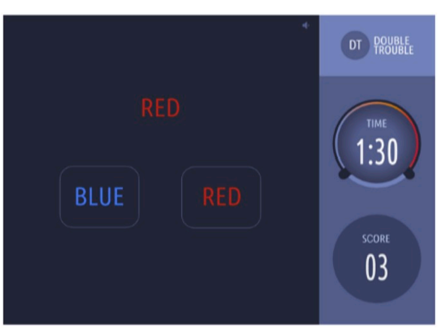
The environmental conditions in both spaces and the sensors (with the accuracy).

Parameter	Measurements		Device	Measurement uncertainty
	With windows	Without windows		
Operative temperature	M = 28.0 °C, SD = 0.21 °C	M = 28.0 °C, SD = 0.15 °C	HOBO data logger (Model U12-012, Onset, USA)	±0.35 °C
Relative humidity	M = 34.8%, SD = 2.5%	M = 34.6%, SD = 2.7%		±2.5%
Air speed	M = 0.02 m/s, SD = 0.00 m/s	M = 0.02 m/s, SD = 0.00 m/s	Sensor-electronic	±0.02 m/s
Horizontal illuminance	M = 461 lux, SD = 39.52 lux	M = 450 lux, SD = 0.1 lux	Licor: Photometric sensor	±5%
CO_2	M = 650 ppm, SD = 130 ppm	M = 680 ppm, SD = 124 ppm	Senseware IAQ package	±25 ppm; ± 3%
Outdoor solar radiation	M = 541 W/m2, SD = 120 W/m2 Min. = 271 W/m2, Max. = 726 W/m2		Li-Cor: Pyranometer	±3% within ±60° angle of incidence
Prevailing mean outdoor temperature*	M = 15.7 °C, SD = 0.8 °C Min. = 14.0 °C, Max = 17.0 °C		RM Young Model: 41372	±0.5 °C

* Prevailing mean outdoor air temperature is calculated based on the arithmetic average of the mean daily outdoor temperatures over some period of days [2]. In this chart, we calculated the temperature based on the mean daily outdoor temperature of seven days before the day in question.

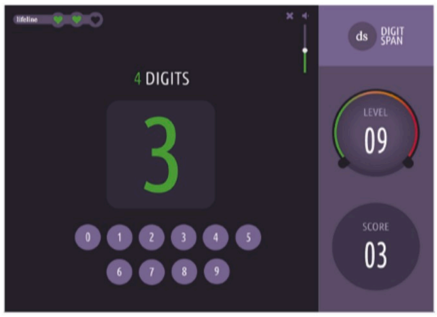
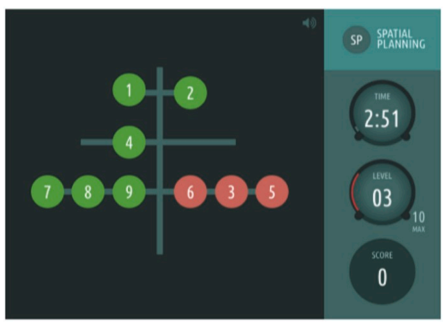
Appendix B

Cognitive tests.

Test	Reference image	Outcome measure	Scoring method
Token Search [110]		Working Memory: the ability to temporarily hold information in memory, and manipulate or update it based on demands	Participants do not have a time limit, but the test will end after three errors. Outcome measure is the maximum level completed (e.g. the problem with the most tokens that the user completed).
Double Trouble [111]		Response Inhibition: the ability to concentrate on relevant information in order to make a correct response despite interference	Participants have 90 s to solve as many problems as possible. The primary outcome measure is the number of correctly answered problems, minus incorrect ones.

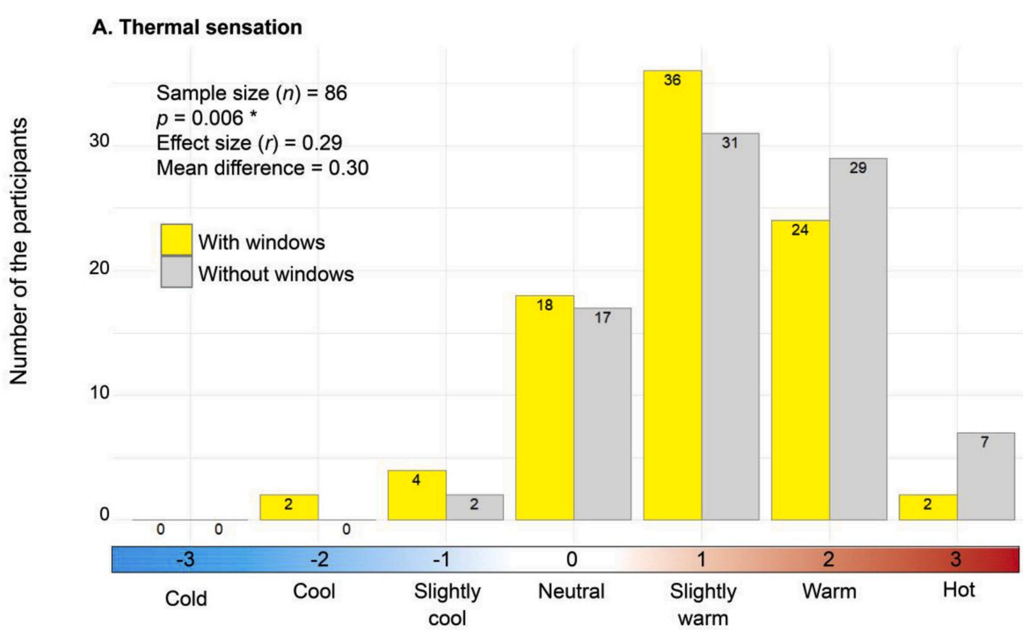
(continued on next page)

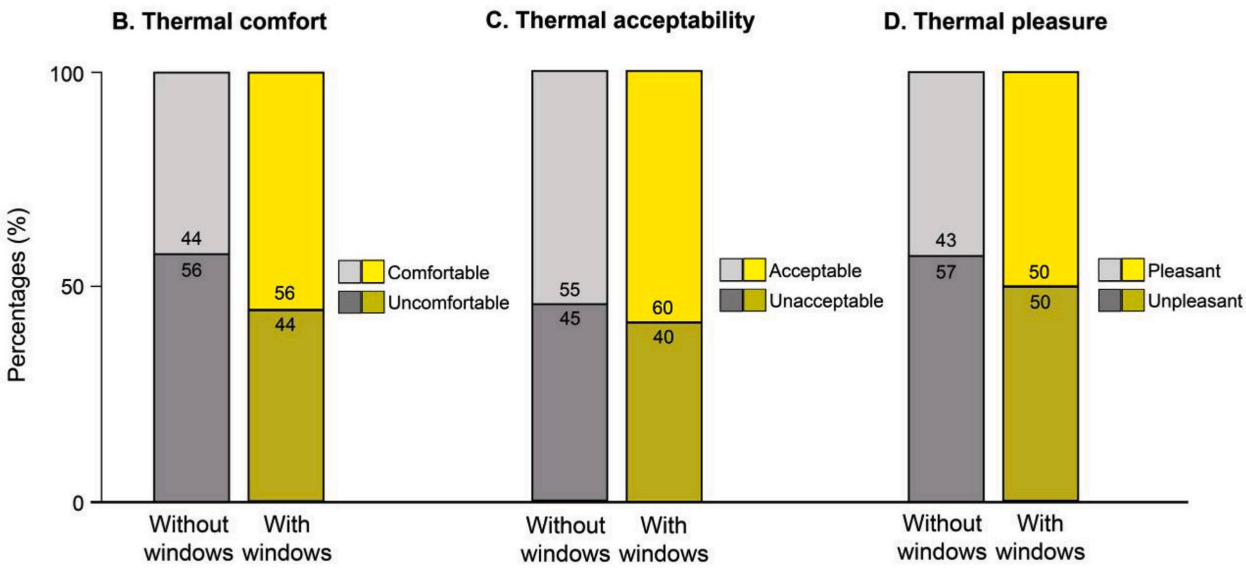
(*continued*)

Test	Reference image	Outcome measure	Scoring method
Digit Span [112]		Short-term memory: the ability to temporarily store information in memory	Participants do not have a time limit, but the test will end after three errors. The primary outcome measure is the maximum level (i.e. the problem with the highest number of digits) that the player completed.
Spatial Planning [63]		Planning: the ability to act with forethought and sequence behavior in an orderly fashion to reach specific goals	Participants have 3 min to solve as many problems as possible. The primary outcome measure is the overall score, calculated by subtracting the number of trials made from twice the minimum number of trials required.

Appendix C

A. The distribution of the Thermal Sensation Vote (TSV) of participants; B. The percentages of the participants who were thermally comfortable or uncomfortable in the experimental conditions; C. The percentages of the participants who reported that the experimental conditions were acceptable or unacceptable; D. The percentages of the participants who felt that the experimental conditions were pleasant or unpleasant.





References

[1] ANSI/ASHRAE, ANSI/ASHRAE Standard 62.1-2016: Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, US, 2016.

[2] ANSI/ASHRAE, ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, US, 2017.

[3] R.J. de Dear, G. Brager, Developing an adaptive model of thermal comfort and preference, Build. Eng. 104 (1998).

[4] L. Huang, Y. Zhu, Q. Ouyang, B. Cao, A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices, Build. Environ. 49 (2012) 304–309, https://doi.org/10.1016/j.buildenv.2011.07.022.

[5] International Code Council, ICC G2-2010 Guideline for Acoustics, 2010.

[6] L.T. Wong, K.W. Mui, P.S. Hui, A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices, Build. Environ. 43 (2008) 1–6, https://doi.org/10.1016/j.buildenv.2007.01.001.

[7] P.M. Bluyssen, S. Janssen, L.H. van den Brink, Y. de Kluizenaar, Assessment of wellbeing in an indoor office environment, Build. Environ. 46 (2011) 2632–2640, https://doi.org/10.1016/j.buildenv.2011.06.026.

[8] M.A. Ortiz, S.R. Kurvers, P.M. Bluyssen, A review of comfort, health, and energy use: understanding daily energy use and wellbeing for the development of a new approach to study comfort, Energy Build. 152 (2017) 323–335, https://doi.org/10.1016/j.enbuild.2017.07.060.

[9] P. Wargocki (Ed.), Indoor Climate and Productivity in Offices: How to Integrate Productivity in Life-Cycle Cost Analysis of Building Services, Rehva, Brussels, 2006.

[10] S.R. Kellert, J. Heerwagen, M. Mador, Biophilic Design: the Theory, Science and Practice of Bringing Buildings to Life, 1 edition, Wiley, Hoboken, N.J, 2013.

[11] E.O. Wilson, Biophilia, Reprint edition, Harvard University Press, Cambridge, Mass., 1984.

[12] Y. Joye, Architectural lessons from environmental psychology: the case of biophilic architecture, Rev. Gen. Psychol. 11 (2007) 305–328, https://doi.org/10.1037/1089-2680.11.4.305.

[13] S. Kellert, E. Calabrese, The Practice of Biophilic Design, 2015. Retrieved Sept. 16 (2015).

[14] C.O. Ryan, W.D. Browning, J.O. Clancy, S.L. Andrews, N.B. Kallianpurkar, Biophilic design patterns: emerging nature-based parameters for health and well-being in the built environment, Int. J. Archit. Res. ArchNet-IJAR. 8 (2014) 62–76, https://doi.org/10.26687/archnet-ijar.v8i2.436.

[15] J.A. Benfield, G.N. Rainbolt, P.A. Bell, G.H. Donovan, Classrooms with nature views: evidence of differing student perceptions and behaviors, Environ. Behav. 47 (2015) 140–157, https://doi.org/10.1177/0013916513499583.

[16] R. Kaplan, The role of nature in the context of the workplace, Landsc. Urban Plann. 26 (1993) 193–201, https://doi.org/10.1016/0169-2046(93)90016-7.

[17] K. Yildirim, A. Akalin-Baskaya, M. Celebi, The effects of window proximity, partition height, and gender on perceptions of open-plan offices, J. Environ. Psychol. 27 (2007) 154–165, https://doi.org/10.1016/j.jenvp.2007.01.004.

[18] M.B.C. Aries, J.A. Veitch, GuyR. Newsham, Windows, view, and office characteristics predict physical and psychological discomfort, J. Environ. Psychol. 30 (2010) 533–541, https://doi.org/10.1016/j.jenvp.2009.12.004.

[19] R. Ulrich, View through a window may influence recovery from surgery, Science 224 (1984) 420–421, https://doi.org/10.1126/science.6143402.

[20] R.S. Ulrich, R.F. Simons, B.D. Losito, E. Fiorito, M.A. Miles, M. Zelson, Stress recovery during exposure to natural and urban environments, J. Environ. Psychol. 11 (1991) 201–230, https://doi.org/10.1016/S0272-4944(05)80184-7.

[21] P. Leather, M. Pyrgas, D. Beale, C. Lawrence, Windows in the workplace: sunlight, view, and occupational stress, Environ. Behav. 30 (1998) 739–762, https://doi.org/10.1177/001391659803000601.

[22] J.E. Dowling, J.L. Dowling, Vision: How it Works and what Can Go Wrong, 1 edition, MIT Press, Cambridge, Massachusetts, 2016.

[23] D. Alais, F.N. Newell, P. Mamassian, Multisensory processing in review: from physiology to behaviour, Seeing Perceiving 23 (2010) 3–38, https://doi.org/10.1163/187847510X488603.

[24] W. Yang, H.J. Moon, Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment, Build. Environ. (2018), https://doi.org/10.1016/j.buildenv.2018.11.040.

[25] M. te Kulve, L.J.M. Schlangen, L. Schellen, A.J.H. Frijns, W.D. van Marken Lichtenbelt, The impact of morning light intensity and environmental temperature on body temperatures and alertness, Physiol. Behav. 175 (2017) 72–81, https://doi.org/10.1016/j.physbeh.2017.03.043.

[26] M. te te Kulve, L. Schlangen, W. van M Lichtenbelt, Interactions between the perception of light and temperature, Indoor Air 28 (2018) 881–891, https://doi.org/10.1111/ina.12500.

[27] G. Chinazzo, J. Wienold, M. Andersen, Daylight affects human thermal perception, Sci. Rep. 9 (2019) 1–15, https://doi.org/10.1038/s41598-019-48963-y.

[28] A. Leaman, B. Bordass, Are users more tolerant of 'green' buildings? Build. Res. Inf. 35 (2007) 662–673, https://doi.org/10.1080/09613210701529518.

[29] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings, Build. Environ. 88 (2015) 89–96, https://doi.org/10.1016/j.buildenv.2014.09.010.

[30] S. Schiavon, A.K. Melikov, Energy saving and improved comfort by increased air movement, Energy Build. 40 (2008), https://doi.org/10.1016/j.enbuild.2008.05.001, 1954–1960.

[31] S.C. Sekhar, Higher space temperatures and better thermal comfort — a tropical analysis, Energy Build. 23 (1995) 63–70, https://doi.org/10.1016/0378-7788(95)00932-N.

[32] L. Yang, H. Yan, J.C. Lam, Thermal comfort and building energy consumption implications – a review, Appl. Energy 115 (2014) 164–173, https://doi.org/10.1016/j.apenergy.2013.10.062.

[33] M.G. Berman, J. Jonides, S. Kaplan, The cognitive benefits of interacting with nature, Psychol. Sci. 19 (2008) 1207–1212, https://doi.org/10.1111/j.1467-9280.2008.02225.x.

[34] R. Berto, Exposure to restorative environments helps restore attentional capacity, J. Environ. Psychol. 25 (2005) 249–259, https://doi.org/10.1016/j.jenvp.2005.07.001.

[35] D.K. Brown, J.L. Barton, V.F. Gladwell, Viewing nature scenes positively affects recovery of autonomic function following acute-mental stress, Environ. Sci. Technol. 47 (2013) 5562–5569, https://doi.org/10.1021/es305019p.

[36] T. Hartig, A. Böök, J. Garvill, T. Olsson, T. Gärling, Environmental influences on psychological restoration, Scand. J. Psychol. 37 (1996) 378–393, https://doi.org/10.1111/j.1467-9450.1996.tb00670.x.

[37] J. Kim, S.H. Cha, C. Koo, S. Tang, The effects of indoor plants and artificial windows in an underground environment, Build. Environ. 138 (2018) 53–62, https://doi.org/10.1016/j.buildenv.2018.04.029.
[38] B.-S. Kweon, R.S. Ulrich, V.D. Walker, L.G. Tassinary, Anger and stress: the role of landscape posters in an office setting, Environ. Behav. 40 (2008) 355–381, https://doi.org/10.1177/0013916506298797.
[39] C.-Y. Chang, P.-K. Chen, Human response to window views and indoor plants in the workplace, Hortscience 40 (2005) 1354–1359, https://doi.org/10.21273/HORTSCI.40.5.1354.
[40] M.G. Berman, E. Kross, K.M. Krpan, M.K. Askren, A. Burson, P.J. Deldin, S. Kaplan, L. Sherdell, I.H. Gotlib, J. Jonides, Interacting with nature improves cognition and affect for individuals with depression, J. Affect. Disord. 140 (2012) 300–305, https://doi.org/10.1016/j.jad.2012.03.012.
[41] T. Hartig, M. Mang, G.W. Evans, Restorative effects of natural environment experiences, Environ. Behav. 23 (1991) 3–26, https://doi.org/10.1177/0013916591231001.
[42] M. Boubekri, I.N. Cheung, K.J. Reid, C.-H. Wang, P.C. Zee, Impact of windows and daylight exposure on overall health and sleep quality of office workers: a case-control pilot study, J. Clin. Sleep Med. JCSM Off. Publ. Am. Acad. Sleep Med. 10 (2014) 603–611, https://doi.org/10.5664/jcsm.3780.
[43] T. Hartig, G.W. Evans, L.D. Jamner, D.S. Davis, T. Gärling, Tracking restoration in natural and urban field settings, J. Environ. Psychol. 23 (2003) 109–123, https://doi.org/10.1016/S0272-4944(02)00109-3.
[44] N.J. Stone, J.M. Irvine, Direct or indirect window access, task type, and performance, J. Environ. Psychol. 14 (1994) 57–63, https://doi.org/10.1016/S0272-4944(05)80198-7.
[45] C.M. Tennessen, B. Cimprich, Views to nature: effects on attention, J. Environ. Psychol. 15 (1995) 77–85, https://doi.org/10.1016/0272-4944(95)90016-0.
[46] E.A. Arens, F.S. Bauman, L.P. Johnston, H. Zhang, Testing of localized ventilation systems in a new controlled environment chamber, Indoor Air 1 (1991) 263–281, https://doi.org/10.1111/j.1600-0668.1991.05-13.x.
[47] F. Bauman, E. Arens, The Development of a Controlled Environment Chamber for the Physical and Subjective Assessment of Human Comfort in Office Environments, 1988. https://escholarship.org/uc/item/0mn5485n. (Accessed 17 September 2019).
[48] T. Hoyt, S. Schiavon, F. Tartarini, T.C.T. Cheung, K. Steinfeld, A. Piccioli, D. Moon, CBE thermal comfort tool for ASHRAE-55, cent, Built. Environ. (2019). UC Berkeley, http://comfort.cbe.berkeley.edu/. (Accessed 14 October 2019).
[49] The Regents of the University of California, Weather Data at Berkeley Lab, Berkeley Lab Weather, 2020. https://sites.google.com/a/lbl.gov/lbnl-meteorological-data/lbnl-weather-data. (Accessed 31 January 2020).
[50] International Organization for Standardization, ISO 9886:2004 Ergonomics – Evaluation of Thermal Strain by Physiological Measurements, second ed., 2004.
[51] S. Kaplan, The restorative benefits of nature: toward an integrative framework, J. Environ. Psychol. 15 (1995) 169–182, https://doi.org/10.1016/0272-4944(95)90001-2.
[52] T. Parkinson, R. de Dear, Thermal pleasure in built environments: physiology of alliesthesia, Build. Res. Inf. 43 (2015) 288–301, https://doi.org/10.1080/09613218.2015.989662.
[53] T. Parkinson, R. de Dear, C. Candido, Thermal pleasure in built environments: alliesthesia in different thermoregulatory zones, Build. Res. Inf. 44 (2016) 20–33, https://doi.org/10.1080/09613218.2015.1059653.
[54] J.A. Russell, A circumplex model of affect, J. Pers. Soc. Psychol. 39 (1980) 1161–1178, https://doi.org/10.1037/h0077714.
[55] D. Watson, A. Tellegen, Toward a consensual structure of mood, Psychol. Bull. 98 (1985) 219–235, https://doi.org/10.1037/0033-2909.98.2.219.
[56] J.W.R. Baur, J.F. Tynon, E. Gómez, Attitudes about urban nature parks: a case study of users and nonusers in Portland, Oregon, Landsc. Urban Plann. 117 (2013) 100–111, https://doi.org/10.1016/j.landurbplan.2013.04.015.
[57] J. Martínez-Soto, L. Gonzales-Santos, F.A. Barrios, M.E.M.-L. Lena, Affective and restorative valences for three environmental categories, Percept. Mot. Skills. 119 (2014) 901–923, https://doi.org/10.2466/24.50.PMS.119c29z4.
[58] M. Boubekri, R.B. Hull, L.L. Boyer, Impact of window size and sunlight penetration on office workers' mood and satisfaction: a novel way of assessing sunlight, Environ. Behav. 23 (1991) 474–493, https://doi.org/10.1177/0013916591234004.
[59] A.C. Weidman, C.M. Steckler, J.L. Tracy, The jingle and jangle of emotion assessment: imprecise measurement, casual scale usage, and conceptual fuzziness in emotion research, Emotion 17 (2017) 267–295, https://doi.org/10.1037/emo0000226.
[60] Cambridge brain sciences (n.d.), https://www.cambridgebrainsciences.com/. (Accessed 30 July 2019).
[61] J. Yin, S. Zhu, P. MacNaughton, J.G. Allen, J.D. Spengler, Physiological and cognitive performance of exposure to biophilic indoor environment, Build. Environ. 132 (2018) 255–262, https://doi.org/10.1016/j.buildenv.2018.01.006.
[62] N. Wang, M. Boubekri, Investigation of declared seating preference and measured cognitive performance in a sunlit room, J. Environ. Psychol. 30 (2010) 226–238, https://doi.org/10.1016/j.jenvp.2009.12.001.
[63] T. Shallice, Specific impairments of planning, Philos. Trans. R. Soc. Lond. B Biol. Sci. 298 (1982) 199–209, https://doi.org/10.1098/rstb.1982.0082.
[64] J.P. Guilford, The Nature of Human Intelligence, McGraw-Hill, New York, NY, US, 1967.
[65] R. Eisenberger, S. Armeli, Can salient reward increase creative performance without reducing intrinsic creative interest? J. Pers. Soc. Psychol. 72 (1997) 652–663, https://doi.org/10.1037/0022-3514.72.3.652.
[66] J.P. Guilford, Creativ. Am. Psychol. 5 (1950) 444–454, https://doi.org/10.1037/h0063487.
[67] P.J. Silvia, B.P. Winterstein, J.T. Willse, C.M. Barona, J.T. Cram, K.I. Hess, J. L. Martinez, C.A. Richard, Assessing creativity with divergent thinking tasks: exploring the reliability and validity of new subjective scoring methods, Psychol. Aesthet. Creat. Arts. 2 (2008) 68–85, https://doi.org/10.1037/1931-3896.2.2.68.
[68] P. Wargocki, D.P. Wyon, J. Sundell, G. Clausen, P.O. Fanger, The effects of outdoor air supply rate in an office on perceived air quality, sick building Syndrome (SBS) symptoms and productivity, Indoor Air 10 (2000) 222–236, https://doi.org/10.1034/j.1600-0668.2000.010004222.x.
[69] K.D. Vohs, J.P. Redden, R. Rahinel, Physical order produces healthy choices, generosity, and conventionality, whereas disorder produces creativity, Psychol. Sci. 24 (2013) 1860–1867, https://doi.org/10.1177/0956797613480186.
[70] J.R. Hayes, J.E. Sheedy, J.A. Stelmack, C.A. Heaney, Computer use, symptoms, and quality of life, Optom. Vis. Sci. 84 (2007), E738, https://doi.org/10.1097/OPX.0b013e31812f7546.
[71] O.D. Brian Chou, Deconstructing the 20-20-20 Rule for Digital Eye Strain, Optom. Times, 2018. https://www.optometrytimes.com/article/deconstructing-20-20-20-rule-digital-eye-strain. (Accessed 4 November 2019).
[72] R.A. Henning, P. Jacques, G.V. Kissel, A.B. Sullivan, S.M. Alteras-Webb, Frequent short rest breaks from computer work: effects on productivity and well-being at two field sites, Ergonomics 40 (1997) 78–91, https://doi.org/10.1080/001401397188396.
[73] P. Vink, S. Hallbeck, Editorial: comfort and discomfort studies demonstrate the need for a new model, Appl. Ergon. 43 (2012) 271–276, https://doi.org/10.1016/j.apergo.2011.06.001.
[74] F. Zhang, R. de Dear, Impacts of demographic, contextual and interaction effects on thermal sensation—evidence from a global database, Build. Environ. 162 (2019), 106286, https://doi.org/10.1016/j.buildenv.2019.106286.
[75] P. Höppe, Different aspects of assessing indoor and outdoor thermal comfort, Energy Build. 34 (2002) 661–665, https://doi.org/10.1016/S0378-7788(02)00017-8.
[76] P.A. Hancock, I. Vasmatzidis, Effects of heat stress on cognitive performance: the current state of knowledge, Int. J. Hyperther. 19 (2003) 355–372, https://doi.org/10.1080/0265673021000054630.
[77] S. Karjalainen, Thermal comfort and gender: a literature review, Indoor Air 22 (2012) 96–109, https://doi.org/10.1111/j.1600-0668.2011.00747.x.
[78] D.P. Wyon, I. Andersen, G.R. Lundqvist, The effects of moderate heat stress on mental performance, Scand. J. Work. Environ. Health 5 (1979) 352–361, https://doi.org/10.5271/sjweh.2646.
[79] S.L. Chellappa, R. Steiner, P. Oelhafen, C. Cajochen, Sex differences in light sensitivity impact on brightness perception, vigilant attention and sleep in humans, Sci. Rep. 7 (2017), https://doi.org/10.1038/s41598-017-13973-1.
[80] J.A. Sherman, Problem of sex differences in space perception and aspects of intellectual functioning, Psychol. Rev. 74 (1967) 290–299, https://doi.org/10.1037/h0024723.
[81] D.F. Halpern, Sex Differences in Cognitive Abilities, third ed., Psychology Press, 2000 https://doi.org/10.4324/9781410605290.
[82] I. Knez, C. Kers, Effects of indoor lighting, gender, and age on mood and cognitive performance, Environ. Behav. 32 (2000) 817–831, https://doi.org/10.1177/0013916500326005.
[83] R.F. Rupp, J. Kim, R. de Dear, E. Ghisi, Associations of occupant demographics, thermal history and obesity variables with their thermal comfort in air-conditioned and mixed-mode ventilation office buildings, Build. Environ. 135 (2018) 1–9, https://doi.org/10.1016/j.buildenv.2018.02.049.
[84] K. Chamilothori, G. Chinazzo, J. Rodrigues, E.S. Dan-Glauser, J. Wienold, M. Andersen, Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality, Build, Environ. Times 150 (2019) 144–155, https://doi.org/10.1016/j.buildenv.2019.01.009.
[85] M.D. Ernst, Permutation methods: a basis for exact inference, Stat. Sci. 19 (2004) 676–685, https://doi.org/10.1214/088342304000000396.
[86] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, 2 edition, Routledge, Hillsdale, N.J, 1988.
[87] C.J. Ferguson, An effect size primer: a guide for clinicians and researchers, Prof. Psychol. Res. Pract. 40 (2009) 532–538, https://doi.org/10.1037/a0015808.
[88] R Core Team, A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, 2018. https://www.R-project.org/.
[89] T. Hothorn, K. Hornik, M.A. van de Wiel, A. Zeileis, Implementing a class of permutation tests: the coin package, J. Stat. Software 28 (2008) 1–23, https://doi.org/10.18637/jss.v028.i08.
[90] IES, The Lighting Handbook, tenth ed., Illuminating Engineering Society, 2011. https://www.ies.org/store/lighting-handbooks/lighting-handbook-10th-edition/. (Accessed 16 January 2018).
[91] D. Griffiths, Thermal Comfort Studies in Buildings with Passive Solar Features Field Studies, the Commission of the European Community, UK, 1990.
[92] M.A. Humphreys, J.F. Nicol, I.A. Raja, Field studies of indoor thermal comfort and the progress of the adaptive approach, Adv. Build. Energy Res. 1 (2007) 55–88, https://doi.org/10.1080/17512549.2007.9687269.
[93] C. Duarte, P. Raftery, S. Schiavon, SinBerBEST technology energy assessment report. https://escholarship.org/uc/item/7k1796zv, 2015. (Accessed 18 December 2019).
[94] A.R. Frisancho, Human Adaptation and Accommodation, University of Michigan Press, 1993.
[95] M.A. Humphreys, Quantifying occupant comfort: are combined indices of the indoor environment practicable? Build. Res. Inf. 33 (2005) 317–325, https://doi.org/10.1080/09613210500161950.

[96] J. Kim, R. de Dear, Nonlinear relationships between individual IEQ factors and overall workspace satisfaction, Build. Environ. 49 (2012) 33–40, https://doi.org/10.1016/j.buildenv.2011.09.022.

[97] M.C. Finnegan, L.Z. Solomon, Work attitudes in windowed vs. Windowless environments, J. Soc. Psychol. 115 (1981) 291–292, https://doi.org/10.1080/00224545.1981.9711674.

[98] Heschong Mahone Group, Windows and Offices: A Study of Office Worker Performance and the Indoor Environment, CEC, Fair Oaks, California, 2003. http://h-m-g.com/downloads/Daylighting/A-9_Windows_Offices_2.6.10.pdf. (Accessed 16 April 2018).

[99] A. Jamrozik, C. Ramos, J. Zhao, J. Bernau, N. Clements, T. Vetting Wolf, B. Bauer, A novel methodology to realistically monitor office occupant reactions and environmental conditions using a living lab, Build. Environ. 130 (2018) 190–199, https://doi.org/10.1016/j.buildenv.2017.12.024.

[100] J. Kim, R. de Dear, Employee satisfaction and the quality of workplace environment, in: Organ. Behav. Phys. Environ, Routledge, 2019, pp. 96–110.

[101] A. Jamrozik, N. Clements, S.S. Hasan, J. Zhao, R. Zhang, C. Campanella, V. Loftness, P. Porter, S. Ly, S. Wang, B. Bauer, Access to daylight and view in an office improves cognitive performance and satisfaction and reduces eyestrain: a controlled crossover study, Build. Environ. 165 (2019), 106379, https://doi.org/10.1016/j.buildenv.2019.106379.

[103] O.A. Seppänen, W. Fisk, Some quantitative relations between indoor environmental quality and work performance or health, HVAC R Res. 12 (2006) 957–973, https://doi.org/10.1080/10789669.2006.10391446.

[104] F. Zhang, R. de Dear, P. Hancock, Effects of moderate thermal environments on cognitive performance: a multidisciplinary review, Appl. Energy 236 (2019) 760–777, https://doi.org/10.1016/j.apenergy.2018.12.005.

[105] R.S. Ulrich, Aesthetic and affective response to natural environment, in: I. Altman, J.F. Wohlwill (Eds.), Behav. Nat. Environ, Springer US, Boston, MA, 1983, pp. 85–125, https://doi.org/10.1007/978-1-4613-3539-9_4.

[106] H. Hellinga, T. Hordijk, The D&V analysis method: a method for the analysis of daylight access and view quality, Build. Environ. 79 (2014) 101–114, https://doi.org/10.1016/j.buildenv.2014.04.032.

[107] B.S. Matusiak, C.A. Klöckner, How we evaluate the view out through the window, Architect. Sci. Rev. 59 (2016) 203–211, https://doi.org/10.1080/00038628.2015.1032879.

[108] J.Y. Shin, G.Y. Yun, J.T. Kim, View types and luminance effects on discomfort glare assessment from windows, Energy Build. 46 (2012) 139–145, https://doi.org/10.1016/j.enbuild.2011.10.036.

[109] D.C. Funder, D.J. Ozer, Evaluating effect size in psychological research: sense and nonsense, Adv. Methods Pract. Psychol. Sci. 2 (2019) 156–168, https://doi.org/10.1177/2515245919847202.

[110] P. Collins, A.C. Roberts, R. Dias, B.J. Everitt, T.W. Robbins, Perseveration and strategy in a novel spatial self-ordered sequencing task for nonhuman primates: effects of excitotoxic lesions and dopamine depletions of the prefrontal cortex, J. Cognit. Neurosci. 10 (1998) 332–354, https://doi.org/10.1162/089892998562771.

[111] J.R. Stroop, Studies of interference in serial verbal reactions, J. Exp. Psychol. 18 (1935) 643–662, https://doi.org/10.1037/h0054651.

[112] J.R. Crawford, K.M. Allan, D.W. Stephen, D.M. Parker, J.A.O. Besson, The Wechsler adult intelligence scale—revised (WAIS-R): factor structure in a U.K. sample, Pers. Indiv. Differ. 10 (1989) 1209–1212, https://doi.org/10.1016/0191-8869(89)90091-3.