An empirical study of occupants' evaluation of short-term combined thermal, visual, and acoustic indoor-environmental exposure

Christiane BERGER* and Ardeshir MAHDAVI

Department of Building Physics and Building Ecology, TU Wien, Vienna, Austria
** Corresponding author: christiane.berger@tuwien.ac.at*

ABSTRACT

Recently, more attention is being paid to human sensation and perception processes under multi-domain indoor-environmental exposure situations. Despite the existing body of research in this area, many more studies must be conducted to elevate the level of our understanding of such processes. In this paper, we present such a study. Thereby, two identical small office units are assembled within a larger laboratory space. Thermal and visual conditions can be separately controlled in these two units. Furthermore, different acoustical conditions can be emulated in the larger laboratory space that houses the two small office units. During the experiments, participants occupy these offices and are exposed to a number of different combinations of indoor-environmental (thermal, visual, and auditory) factors. A key query thereby is as follows: Are identical thermal conditions evaluated differently given interference attributable to other exposure variables (e.g., glare, noise). The paper presents the research design and the results.

INTRODUCTION AND BACKGROUND

Recently, increased attention is being paid to human sensation and perception processes under multi-domain indoor-environmental exposure situations. The term "multi-domain" denotes here the simultaneous presence of various indoor-environmental factors, including thermal, visual, auditory, and olfactory influences. It can be of course argued that common indoor-environmental situations are multi-domain as a matter of course (Mahdavi et al. 2020a, b).

Nonetheless, the majority of codes, standards, and guidelines for building design and operation have a single-domain character, in that they address such domains in isolation. Consequently, there are separate sets of performance targets and requirements for each of the indoor-environmental domains.

There has been a number of past research efforts that include valuable contributions with regard to multi-domain exposure situations (Mahdavi et al. 2020a). For instance, a study by Tiller et al. (2010) suggested that acoustical conditions influence somewhat the subjective ratings of thermal comfort. But they could not document an effect in the opposite direction. Auditory comfort votes were found to be slightly influenced by operative temperature (Nagano and Horikoshi 2005). However, in this study, noise was not observed to have an effect on reported thermal sensation. Interestingly, Pellerin and Candas (2003) suggested that thermal comfort is influenced by noise under warmer conditions. However, temperature was not found to influence acoustic sensation, comfort, and preference. On the other hand, Yang and Moon (2018) observed a decrease in reported thermal comfort when noise levels increased. They included two kinds of acoustical background, namely babble and fan noise. The former was judged to be louder as compared to the latter.

Despite these and other efforts (Yang et al. 2019, Yang and Moon 2018, Winzen et al. 2014, Azmoon et al. 2013, Tiller et al. 2010, Nagano and Horikoshi 2005, Pan et al. 2003, Pellerin and Candas 2003, Nakamura and Oki 2000), the explanatory power of their results remains limited and inconclusive. One of the reasons for this circumstance may be the considerable complexity of the physiological and psychological processes that are relevant to building occupants' perception and evaluation of indoor environments (Mahdavi 2020). To elevate the level of our understanding of such processes, many more studies must be conducted.

The present paper describes such a study (Berger and Mahdavi 2021). Thereby, within a large laboratory space, two identical small office units are assembled. Thermal and visual (lighting) conditions can be separately controlled in these two units. Specifically, values of ambient air temperature and air relative humidity can be modified. Likewise, it is possible to use different combinations of luminaires to influence both task illuminance and effective glare levels. Furthermore, different acoustic conditions (e.g., traffic noise) can be emulated in the larger laboratory space that houses the two small office units.

During the experiments, participants occupy these offices on a short-term basis and are requested to conduct common office-type tasks. Thereby, the participants are exposed to a number of different combinations of indoor-environmental (thermal, visual, and auditory) factors.

Subsequent to an initial adaptation phase, participants are requested to evaluate the ambient conditions with regard to thermal comfort, lighting, and acoustics.

A key query thereby is as follows: Are identical thermal conditions evaluated differently by participants given interference attributable to other exposure variables (e.g., glare, noise).

The paper briefly presents the research design and some preliminary results. A key finding of the study pertains to the question if and to which extent participants, who experience the same thermal conditions but different lighting and/or acoustical circumstances, differ in their thermal comfort evaluation.

APPROACH

Settings

The experiments were conducted in a laboratory space containing two similar mock-up offices, each with four workplaces (see Figure 1). The offices receive no daylight and are mechanically ventilated. During the experiments, indoor air temperature and humidity, globe temperature, air flow speed, CO2 concentration, illuminance, glare intensity (expressed in terms of UGR), and sound pressure level were measured. In certain instances, the emulated traffic noise was emitted via a loudspeaker system located in the larger laboratory space that houses the two mock-up spaces.

Participants

The experiments involved 189 females and 107 male participants (mostly healthy students between 21 and 26 years of age). The mean clo-value of the participants' clothing was, depending on the season, between 0.5 and 0.8. During the experiments, participants engaged in sedentary activity (estimated metabolic rate = 1 met). Controlling the devices such as thermostats or light switches or interactions among the participants was not part of the research design.

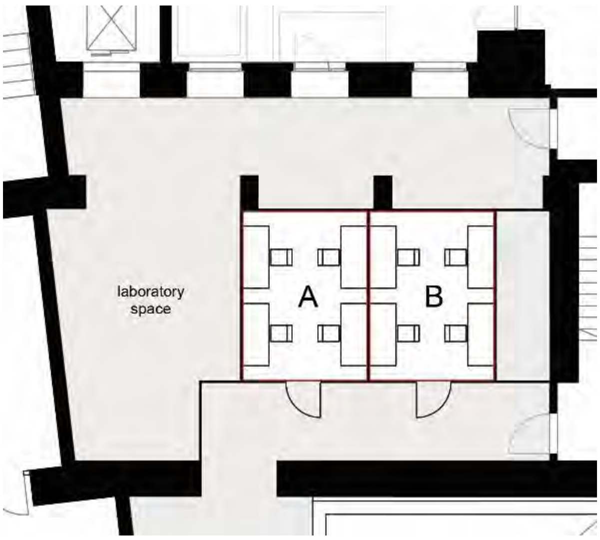

Figure 1. Schematic plan of the general laboratory space and the two mock-up office spaces marked as A and B (based on Berger and Mahdavi 2021, modified)

Indoor environment scenarios

Twelve indoor-environmental scenarios were realized involving various combinations of thermal, visual, and auditory conditions. Table 1 provides a summary of these scenarios.

To examine these scenarios, a between-subject experiment was conducted, whereby participants were randomly assigned to one of the twelve scenarios. Thereby, "T", "V", and "A" signify thermal, visual, and auditory conditions.

With regard to temperature, three conditions were maintained ("T1" = 23.5°C, "T2" = 24.5°C, and "T3" = 25.5°C). Two visual settings were maintained. The distinction between these two conditions can be expressed numerically using the concept of Unified Glare Rating (UGR) (Sorensen 1987). The glare-free condition is denoted as "V1" (UGR = 3.4), whereas the condition involving glare is denoted as "V2" (UGR = 19.8).

Two distinct auditory settings were realized as well, namely a relatively quiet setting "A1" and a relatively louder setting "A2". The measured A-weighted sound level for the first setting was 40 dB, whereas the measured value for the louder setting that involved traffic noise was 61 dB.

The experiments were conducted both in winter (2018/2019) and summer (2019). The participants' exposure to these twelve conditions was counterbalanced such that all scenarios occurred equally often in the morning and the afternoon.

Procedure

The experimental procedure was as follows. Subsequent to a brief adaptation and introduction phase, participants were exposed to one of the scenarios for about 40 minutes. They performed typical office work and completed a number of questionnaires. The first was about background information (age, gender, etc.) and the subsequent ones captured participants' subjective thermal, visual, and acoustic sensation and comfort. Thereby, a 7-point sensation scale ("cold", "cool", "slightly cool", "neutral", "slightly warm", "warm", and "hot") and a 6-point comfort scale ("very uncomfortable", "uncomfortable", "slightly uncomfortable", "slightly comfortable", "comfortable", "very comfortable") was used.

As shown in Table 2, the assigned numeric values to the thermal sensation scale are from -3 (cold) to +3 (hot). Those assigned to the thermal comfort scale are from 1 (very uncomfortable) to 6 (very comfortable). Similar scales were used for visual (from very dark to very bright) and auditory evaluations (from very loud to very quiet).

The key research question

The collected data was processed to address the following main research question:

Are participants' thermal sensation response to and thermal comfort evaluations of the same thermal conditions influenced by a difference in visual and/or auditory conditions?

As alluded to before, the differences in visual and auditory conditions were realized via two distinctive settings for each domain, that is with and without glare in the visual domain and with and without traffic noise in the auditory domain.

Table 1. Specification of the experimental scenarios in terms of the prevailing ambient air temperature, glare rating (UGR), and A-weighted sound pressure level (based on Berger and Mahdavi 2021)

Scenario	Temperature [°C]	UGR	L [dB(A)]
T1V1A1	23.5 ±0.5	3.4	40
T1V1A2	23.5 ±0.5	3.4	61
T1V2A1	23.5 ±0.5	19.8	40
T1V2A2	23.5 ±0.5	19.8	61
T2V1A1	24.5 ±0.5	3.4	40
T2V1A2	24.5 ±0.5	3.4	61
T2V2A1	24.5 ±0.5	19.8	40
T2V2A2	24.5 ±0.5	19.8	61
T3V1A1	25.5 ±0.5	3.4	40
T3V1A2	25.5 ±0.5	3.4	61
T3V2A1	25.5 ±0.5	19.8	40
T3V2A2	25.5 ±0.5	19.8	61

Table 2. Descriptive statistics of thermal, visual, and auditory evaluation scales (Berger and Mahdavi 2021)

Numeric value	Descriptive characteristics		
	Thermal sensation	Visual sensation	Acoustic sensation
-3	cold	very dark	very loud
-2	cool	dark	loud
-1	slightly cool	rather dark	rather loud
0	neutral	neutral	neutral
+1	slightly warm	rather bright	rather quiet
+2	warm	bright	quiet
+3	hot	very bright	very quiet

RESULTS

As mentioned previously, the central objective of the study was to see if participants' thermal evaluation would be affected by presence of glare and/or noise. Table 3 summarizes the results for all scenarios. It includes participants' subjective evaluations on thermal comfort and thermal sensation in terms of mean values and standard errors.

Figures 2 and 3 illustrate the distribution of participants' thermal sensation and comfort evaluations for all three temperature ranges (T1, T2, T3). The x-axis in these figures reflect the participants' thermal sensation and comfort votes. The y-axis shows the fraction of the total votes (from zero to one) corresponding to participants' rating. In these figures, the results are displayed in terms of four groups, namely V1A1, V1A2, V2A1, and V2A2. Thereby, each of these four groups entail the outcome of all three temperature ranges (see also Table 1).

The statistical analysis of these findings (as entailed in Table 3 and illustrated in Figures 2 and 3) in terms of descriptive statistics does not reveal a noteworthy impact of visual or auditory gradients of the exposure situation on the participants' thermal sensation votes. Concerning thermal comfort evaluations, a minor effect of the noise factor may be discerned, both on its own ("V1A2"), or in conjunction with glare ("V2A2").

In summary, this study could not provide a conclusive and statistically significant evidence for a cross-modal influence of visual and auditory factors on participants' thermal sensation and comfort evaluations.

Table 3. Mean values (μ) and standard errors (SE) of participants' thermal sensation and comfort evaluations (based on Berger and Mahdavi 2021)

Scenarios	Thermal sensation		Thermal comfort	
	μ	SE	μ	SE
T1V1A1	0.45	0.17	4.27	0.18
T1V1A2	0.04	0.17	4.05	0.18
T1V2A1	0.09	0.20	3.87	0.23
T1V2A2	0.47	0.17	4.18	0.15
T2V1A1	0.46	0.18	4.23	0.17
T2V1A2	0.33	0.17	4.08	0.19
T2V2A1	0.58	0.15	3.92	0.21
T2V2A2	0.10	0.13	3.81	0.17
T3V1A1	0.46	0.14	3.85	0.20
T3V1A2	0.66	0.13	3.47	0.15
T3V2A1	0.64	0.15	4.12	0.19
T3V2A2	0.83	0.21	3.50	0.20

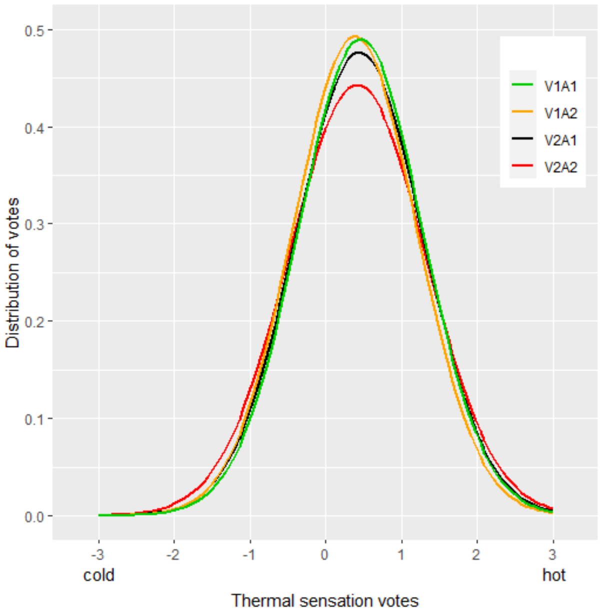

Figure 2. Participants' thermal sensation evaluation (all temperature ranges) (Berger and Mahdavi 2021)

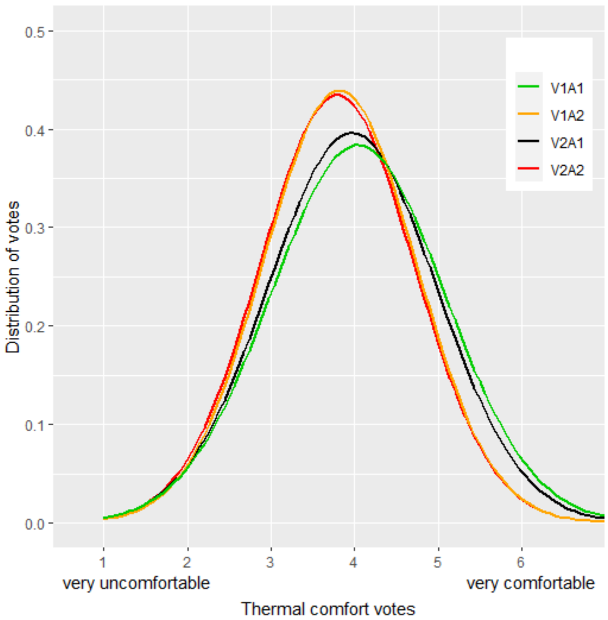

Figure 3. Participants' thermal comfort evaluation (all temperature ranges) (Berger and Mahdavi 2021)

DISCUSSION

The statistical analysis of the results, participants' thermal sensation and comfort votes, did not reveal any clearly discernible cross-modal effects. As such, from the present study, the subjective evaluation of similar thermal conditions cannot be suggested to have been significantly influenced by elevated levels of visual or auditory exposure.

Given the absence of non-overlapping ranges around mean tendencies of the votes in various treatments, it is unlikely that purely short-term studies in emulated settings and with limited parametric constellations, no matter how carefully designed and executed, could expose strong signals of cross-domain effects on building occupants' indoor-environmental perception and comfort evaluations.

However, we do not suggest that the results of this study can be used to make ultimate judgments about the existence and scope of cross-modal effects in realistic situations. This is mainly due to the limitations of the study. Even though the experiments profited from a fairly large group of 296 participants, the sample cannot be suggested to be representative. Specifically, the sample's coverage in view of participants' age, occupation, health, and cultural background was rather restricted. The thermal preferences of a broader and more diverse group of participants could have been conceivably different.

Aside from the limitations of the sample, the experimental research design faced other challenges as well. For instance, we cannot exclude potential effects of the so-called Hawthorne effect. As such, participants did not know the details of the study's ultimate objectives. But they could fathom they were not to be in real offices and that they were being observed. Another limitation of the study pertains to the small number of scenarios we could accommodate in the research design. We could only look at three thermal ranges, two visual states, and two auditory states.

A further – and significant – limitation concerns an issue that is not singular to our study but lies in the logic of short-term occupancy studies. In such studies, participants are initially unfamiliar with the surroundings and may have insufficient time for full adjustment and adaptation, both physiologically and psychologically.

This limits the possibility to make inferences from the findings of short-term studies to more realistic and long-term occupancy circumstances in real-life indoor settings.

CONCLUSION

We presented the results of laboratory-based short-term experiments with 296 participants in two mock-up offices. The objective of these experiments was to examine possible cross-domain effects resulting from indoor-environmental exposure. Thereby, we focused on possible effects of changes in visual and/or auditory factors on participants' evaluation of thermally similar conditions. As such, in the course of these controlled short-term experiments, participants experienced similar thermal conditions but different auditory (with and without traffic noise) and visual (with and without glare) circumstances.

The statistical analysis of the participants' thermal sensation and comfort evaluations did not show a significant cross-modal influence of visual and auditory factors. However, as mentioned in the previous discussion, the study entails a number of limitations. These limitations must be considered in the course of preparation of further future investigations (Berger and Mahdavi 2021). For instance, larger and more diverse samples of participants are needed. Necessary are likewise larger and more diverse array of configurations concerning the indoor-environmental variables in multiple domains. Moreover, more long-term studies in more realistic settings need to be conducted, ideally in a variety of building types. As such, the application of field study techniques could be useful.

At the opposite end of the spectrum of research efforts, specialized and highly controlled laboratory studies with neuro-physiological focus could explore, in more depth, causal mechanisms relevant to multi-sensory information processing relevant to human sensation, perception, evaluation, and behaviour. This observation highlights the urgent need for more intensive multidisciplinary and collaborative (both field and laboratory) studies, such that a more comprehensive pallet of indoor-environmental conditions could be investigated and appropriate ramifications for practical applications could be inferred.

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