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Environmental Conditions and Occupant Satisfaction in the Workplace: A Controlled Study in a Living Lab

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ABSTRACT
Living labs offer a powerful, new way to measure human-building interactions. In addition to having the advantages of a traditional controlled laboratory setting, living labs facilitate the study of how combinations of environmental factors directly affect human health and satisfaction in a real-world setting. The aim of this experimental study was to characterize the relationship between individual-level exposure to environmental conditions and reported satisfaction with environmental quality in a simulated open-office workspace created in a living lab. Eight office workers were exposed to six different week-long combinations of light (natural and electric), sound, and thermal conditions over 18 weeks in a living lab. We assigned exposure to temperature, relative humidity, and light, specifically illuminance, to each participant using measurements from the environmental sensor in closest proximity to the participant. Sound measurements were collected by only one device, so all participants were assigned the same sound exposure. Participants also completed daily questionnaires in which they rated their level of satisfaction with the overall quality of the workplace and with specific environmental parameters in the simulated workspace. Using ordinal response mixed effects models, we found that temperature, noise, and light — individually and in combination — were significant predictors of self-reported occupant satisfaction. Our results contribute to a better understanding of the relative importance of environmental parameters to employee satisfaction in a real-world context, which may be useful for guiding and optimizing building design and management decisions to best serve its occupants.

KEYWORDS
Controlled-study, IEQ, Living lab, Satisfaction, Workplace

INTRODUCTION

An active area of research at the intersection of building sciences, health sciences, and behavioural sciences is understanding the relative impact of different environmental conditions on satisfaction with the indoor environment. This is important because environmental conditions are key determinants of occupant comfort and satisfaction, as well as health, well-being, and performance (Wargocki et al. 2000; Veitch et al. 2008; Lan et al. 2012; Al Horr et al. 2016; MacNaughton et al. 2017; Tanabe et al. 2014; Geng et al. 2017; Küller et al. 2006). Living labs, defined as research settings in which study participants occupy a simulated environment for an extended period of time, are well-positioned to collect this information. Living labs enable the delivery of combinations of environmental conditions, while providing the scientific rigor of an experimental study and the real-world applicability of an observational study.

The aim of this study was to examine the association between exposure to environmental conditions and reported satisfaction with environmental quality in a simulated open-office workspace created in a living lab. This study is also an extension of a proof-of-concept study previously reported by Jamrozik (2018) that found that changes in environmental office conditions affected occupants' experiences inside and outside of the space. In contrast to Jamrozik et al.'s scale of analysis at the level of weeklong "scenes" – combinations of acoustic, lighting, and thermal conditions, this study examined the daily-level relationship between individual exposure to these combinations of environmental conditions and reported satisfaction with office environmental quality. This approach was undertaken for two reasons: 1) doing so enabled an analysis at increased temporal granularity (i.e., from the average response over multiple weeks to the daily scale), and 2) actual exposure values may differ day-to-day and between weeks despite having identical scene conditions and setpoints.

METHODS

Study design

The Well Living Lab is a research facility consisting of six experimental modules that can be configured to simulate real-world indoor environments (Jamrozik et al. 2018). In this study, three of the fabric modules (Modules D, E, and F) were combined to form a 124 m^2 open office (Figure 1), which served as the experimental setting for six environmental "scenes" made up of combinations of acoustic, lighting, and thermal conditions. A baseline condition (scene 1) was designed based on existing research and the participants' previous office in order to simulate environmental conditions commonly found in an average office setting.

Figure 1 shows the layout of the modules where eight office workers sat at desks 1-4 and 6-9 and worked in the simulated office, where they were exposed to week-long combinations of natural light (three levels), electric light (four levels), sound (five levels), and temperature (three levels) (Table 1). A nine-week sequence of scenes (order: 1, 2, 3, 4, 1, 2, 5, 6, 2) was repeated twice over a period of eighteen weeks, from May 31, 2016 to September 30, 2016.

Acoustic, lighting, and thermal conditions

Using the Center for the Built Environment Thermal Comfort tool, assuming a mean radiant temperature of 26.0°C, a wind speed of 0.1 m/s, relative humidity (RH) of 45%, a metabolic rate of 1.1 met, and a clothing level of 0.7 clo (Hoyt et al. 2017), three temperature setpoints were chosen for this experimental study: 21.7°C (cool-neutral temperature), 23.9°C (neutral-warm), and 19.4°C (uncomfortably cold). Additionally, study participants were exposed to five acoustic conditions including sound masking via white noise (two conditions), sound masking via simulated speech (two conditions), and no sound masking.

To vary participant exposure to natural light, windows were equipped with electrochromic (EC) glass (VIEW Dynamic Glass, Inc.) which provided controllable window tinting. Sheer shades (Phifer SheerWeave 4100, 10%, Alabaster – motorized by Lutron) provided occupants a means of controlling natural light via wall switches next to windows, and blackout shades (Mermet Blackout-White – motorized by Lutron) were used to simulate a windowless office. The EC glass tint varied between clear (visible transmittance 58%), dark (visible transmittance 1%), and intelligence mode, in which tint level is automated and varied over four levels throughout the day to limit glare and reduce solar heating. For electrical lighting (S30, Ketra), the following color correlated temperature (CCT) setpoints were used: 2700°K (warm colour), 3500°K (warm-neutral white), 4200°K (cool-neutral white), and 6500°K (cool white).

Participants

The eight participants recruited for this study were employees of the Mayo Clinic in Rochester, Minnesota, all of whom were adults between the ages of 18 and 65 years, able to conduct current work duties from a remote location (i.e., the living lab), and able to work 20-40 hours per week. Full inclusion and exclusion criteria for study participants have been previously described in detail by Jamrozik (2018). One participant (located at desk 4) was removed from the data set due to sensor connection issues, leaving a total of seven participants for inclusion in the data analysis (mean age = 46.9 years, standard deviation (SD) = 13.1). The study was approved by the Mayo Clinic Institutional Review Board.

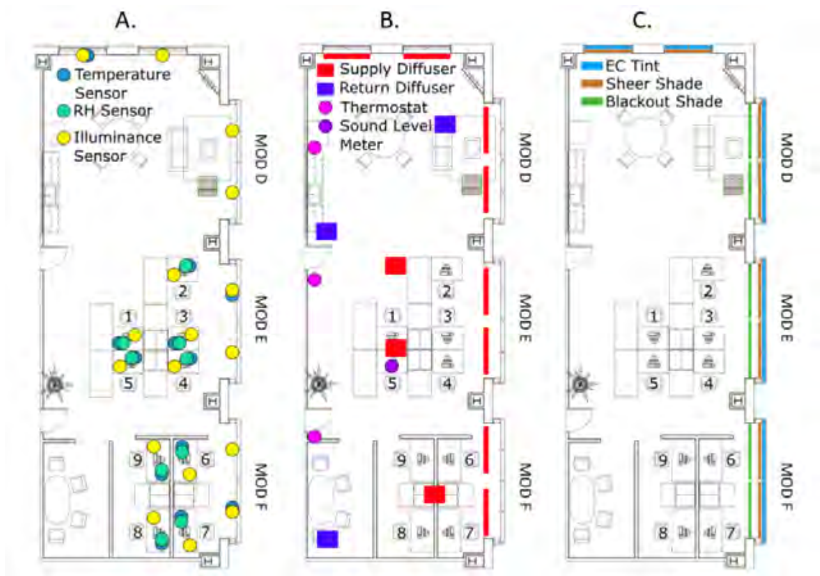

Figure 1. Layout of the experiment space and locations of a) temperature, relative humidity (RH), and illuminance sensors, b) thermostats, sound level meter, and ventilation diffusers, and c) electrochromic (EC) tint glass, sheer shades, and blackout shades. Participants were located at desks 1-4 and 6-9.

Survey design

At the start of the study, participants completed a baseline survey asking about demographics, work, and health behaviors. At the end of each day, participants completed questionnaires asking about satisfaction with environmental conditions and their overall work experience for the day, as well as their mood and health behaviors. In this study, we focused our analysis on daily ratings of overall workplace quality (How much did your work environment make it easy for you to get your work done? 1-5 scale; 1: Not at all, 5: Very much) and satisfaction with the noise level, lighting, and temperature (Today, how satisfied are you with the __ in the work environment? 1-5 scale; 1: Very dissatisfied; 5: Very satisfied).

Data collection, processing and analysis

At desk-level, wireless temperature and humidity sensors (Wireless Humidity Sensor, Monnit Corp.) collected data at five-minute intervals, and wireless horizontal illuminance sensors (Lux1000 Light Level Sensor, Wovyn LLC) collected data at ten-minute intervals. Sound level was measured every ten seconds by a single sound level meter (XL2 Audio and Acoustic Analyzer with M2211 Microphone, NTi Audio Inc.) located at desk 5. Because of connection issues for the temperature and RH sensor located at desk 4, which resulted in missing data, all information collected from the participant located at desk 4 was excluded from the analysis.

The calculation of average daily exposure was restricted to measurements collected between 7:00 and 17:00 CDT because participants' usual working hours were 6:30 to 17:30 CDT. We performed ordinal mixed effects regression analyses using the 'ordinal' package in R (Version 3.4.0). Day of the week, calendar date, and study week were assessed for confounding and not included in the final models. Final models included sound level, illuminance, temperature, and RH (all as continuous variables), an indicator for study scene, and a random intercept for study participant. The number of quadrature points in the adaptive Gauss-Hermite approximation was set to 10 to improve the accuracy of maximum likelihood estimates. To facilitate direct comparison across environmental conditions, odds ratios (ORs) and 95% confidence intervals (CIs) are reported for a normalized unit of exposure, i.e., a one standard deviation (SD) change in estimated exposure, assuming a linear exposure-response function.

RESULTS

Overall (across the six experimental scenes), mean (± SD) desk-level temperature and RH was 24.1°C (± 1.7) and 42.9% (± 5.8), respectively, and mean illuminance was 778.2 lx (± 692.8). Measured desk-level temperatures were, on average, higher than setpoints by 1.2 to 3.1°C. Mean RH across different scenes ranged from 37.6% (± 3.0) to 48.6% (± 4.5). Substantial variation was observed in mean illuminance between and within scenes, with estimates ranging from 413.1 lx (± 495.0) to 1001.8 lx (± 622.5). The mean sound level was 47.1 dBA (± 1.0) and showed little variation between scenes, although measured sound levels were loudest for the two scenes in which sound masking was white noise (Table 1).

Workplace quality satisfaction

Using ordinal response mixed effects models, we found that lower measured illuminance was significantly associated with greater workplace quality satisfaction and greater satisfaction with sound levels (Table 2). Additionally, greater measured overall volume was significantly predictive of increased satisfaction with overall workplace quality, sound levels, and temperature. Higher measured temperature was also significantly associated with increased satisfaction with temperature. We did not observe any significant associations for reported satisfaction with lighting. Although convergence criteria for all models were met, the condition number of the Hessian exceeded 10^7, which indicates that models were not well-defined and should be interpreted with caution. The large variability in illuminance in this study likely contributed to the observed lack of empirical identifiability (e.g., scaling issues).

DISCUSSION

Utilizing a living lab designed to simulate an open office workspace, we found that measured illuminance and sound were significantly predictive of satisfaction with overall workplace quality, and that this pattern was also true for satisfaction with sound levels. However, in contrast to these results, none of the four examined environmental parameters were associated with reported satisfaction with lighting. Additionally, we found that measured temperature and sound were significantly associated with satisfaction with temperature.

As reported previously by Jamrozik (2018), when participants were asked whether they were more sensitive to certain environmental conditions than to others, they most frequently reported that cold temperatures were the most noticeable and unpleasant conditions, followed by noise, and then lack of daylight. This analysis complements the previous qualitative findings, by quantifying the link between individual-level exposure to environmental conditions and reported satisfaction with environmental quality. However, based on model performance metrics, the magnitude and direction of our results should not be interpreted as indicative of the relative importance of environmental conditions nor of the direction of the

Table 1. Description of building system set points and mean (± SD) environmental conditions, by study scene (weekdays from 7:00 to17:00 CDT).

Scene No.	Total Days	EC Glass (Tint No.)	Sheer Shades (Blackout Shades)	Light CCT (°K)	Light Illuminance (Lx)	Relative Humidity (%)	Temperature (°C)		Sound Masking (dBA)	
					Measured	*Measured*	*Setpoint*	*Measured*	*Setting*	*Measured*
1 (Baseline)	19	Clear (Tint 1)	Open, Controllable (Open)	3500	999.6 (± 690.4)	40.3 (± 3.7)	21.7	24.8 (± 1.2)	Off	46.9 (± 0.9)
2	28	Intelligence (Tints 1-4)	Open, Controllable (Open)	4200	703.0 (± 675.4)	43.0 (± 6.2)	21.7	23.9 (± 1.4)	Off	47.0 (± 0.9)
3	10	Dark (Tint 4)	Closed, Inoperable (Closed)	2700	413.1 (± 495.0)	48.1 (± 3.8)	19.4	22.4 (± 1.4)	White Noise (Low)	47.2 (± 0.8)
4	10	Clear (Tint 1)	Open, Controllable (Open)	2700	1001.8 (± 622.5)	37.6 (± 3.0)	23.9	26.0 (± 1.2)	Simulated Speaking I	47.1 (± 1.0)
5	10	Dark (Tint 4)	Closed, Inoperable (Closed)	6500	695.0 (± 801.4)	48.6 (± 4.5)	19.4	22.3 (± 1.1)	White Noise (High)	47.6 (± 1.3)
6	10	Intelligence (Tints 1-4)	Open, Controllable (Open)	6500	752.3 (± 654.8)	40.8 (± 3.4)	23.9	25.1 (± 0.9)	Simulated Speaking II	46.7 (± 0.9)

Table 2. Odds ratios (OR) and 95% confidence intervals (CI) of reporting higher satisfaction associated with a 1 SD change* in environmental conditions.

Environmental Parameters in Model	Satisfaction with Workplace Quality OR (95% CI)	Satisfaction with Acoustics OR (95% CI)	Satisfaction with Temperature OR (95% CI)	Satisfaction with Lighting OR (95% CI)
Light (Illuminance)	6.3 (1.5, 26.0)†	4.7 (1.7, 13.2)‡	1.6 (0.6, 4.1)	1.4 (0.5, 3.7)
Sound	1.4 (1.1, 1.9)†	1.3 (1.03, 1.7)†	1.4 (1.1, 1.7)‡	0.9 (0.7, 1.2)
Temperature	1.2 (0.8, 1.8)	1.4 (0.9, 2.0)	1.5 (1.05, 2.0)†	0.9 (0.7, 1.3)
Relative Humidity	1.04 (0.96, 1.1)	1.0 (0.94, 1.1)	1.1 (0.99, 1.12)	1.0 (0.95, 1.1)

* +1 SD change for sound, temperature, and relative humidity. -1 SD change for light.

† P-value < 0.05; ‡ P-value < 0.01

relationships. Accordingly, although we observed interesting associations between environmental parameters and satisfaction with other parameters (e.g., light was predictive of satisfaction with acoustics; sound was predictive of satisfaction with temperature), these findings may be due to multi-collinearity since exposure was experimentally delivered in scene combinations. Nonetheless, our results support a link between temperature, noise, and light and satisfaction with workplace quality and/or indoor environmental conditions.

CONCLUSIONS

In this study we demonstrate that living labs can be used to identify the environmental conditions predictive of higher self-reported satisfaction with overall workplace quality, and with specific workplace ambient conditions. We found that temperature, noise, and light are important, predictive factors of occupant satisfaction, consistent with prior studies. Future studies should examine more combinations of environmental parameters in a real-world setting, in order to generate evidence that may guide and optimize building design and management decisions to best serve occupants.

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REFERENCES

Al Horr Y., Arif M., Kaushik A., Mazroei A., Katafygiotou M., and Elsarrag E. 2016. Occupant productivity and office indoor environment quality: A review of the literature. *Building and Environmen*t, 105, 369-389.

Hoyt T., Schiavon S., Piccioli A., Cheung T., Moon D., and Steinfeld K. 2017. CBRE Thermal Comfort Tool for ASHRAE-55. Center for the Built Environment, University of California Berkeley. http://comfort.cbe.berkeley.edu/

Geng, Y., Ji W., Lin B., and Zhu Y. 2017. The impact of thermal environment on occupant IEQ perception and productivity. *Building and Environment*, 121, 158-167.

Jamrozik A., Ramos C., Zhao J., Bernau J., Clements N., Wolf T. V., and Bauer B. 2018. A novel methodology to realistically monitor office occupant reactions and environmental conditions using a living lab. *Building and Environment*, 130, 190-199.

Küller R., Ballal S., Laike T., Mikellides B., and Tonello G. 2006. The impact of light and colour on psychological mood: a cross-cultural study of indoor work environments. *Ergonomics*, 49(14), 1496-1507.

Lan L., Wargocki P., and Lian Z. 2012. Optimal thermal environment improves performance of office work. *REHVA Journal*, 49(1), 12-17.

MacNaughton P., Satish U., Laurent J.G.C., Flanigan S., Vallarino J., Coull B., Spengler J.D., and Allen J.G. 2017. The impact of working in a green certified building on cognitive function and health. *Building and Environment*, 114, 178-186.

Tanabe S.I., Haneda M., Nishihara N. 2014. Workplace productivity and individual thermal satisfaction. *Building and Environment*, 91, 42-50.

Veitch J.A., Charles K.E., Farley K.M., and Newsham G.R. 2007. A model of satisfaction with open-plan office conditions: COPE field findings. *Journal of Environmental Psychology*, 27(3), 177-189.

Wargocki P., Wyon D.P., Sundell J., Clausen G., and Fanger, P. 2000. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air*, 10(4), 222-236.