buildings

Supplemental Information

The spatial and temporal variability of the indoor environmental quality during three simulated office studies at a living lab

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Surface Temperature Spatial Assessment

During the Daylighting Study, wall and window (i.e. shade) surface temperatures were measured using an infrared camera (E5, FLIR Systems, Inc.) during one day for each of the following combinations of conditions, if they occurred during the experiment: temperature (high temperature in the 70's, 80's, or 90's °F), cloudiness (sunny, partially overcast, overcast, or raining), and experimental condition (Baseline, Mesh Shades, Dynamic Tint). Samples were collected every two hours between 09:00 and 17:00 at each window (W01-W08), at one central point along the south wall, at three points along the west wall corresponding to the center of each module, and at the floor and ceiling near the center of each module (18 total sampling points). Surface temperature data were averaged by location (East Windows, North Windows, Walls/Floors/Ceilings) for comparisons of temporal variability and weather conditions.

Natural Light Spatial Assessment

During the Multi-IEQ Study, natural lighting was assessed during: 1. Morning with tint at level 1 and mesh shades open, 2. Morning with tint at level 4 and mesh shades open, 3. Morning with tint at level 1 and mesh shades closed, 4. Afternoon with tint at level 1 and shades open, and 5. Afternoon with tint at level 1 and mesh shades closed.

Natural lighting was assessed during the Daylighting Study during morning and afternoon with façade set to: 1. Tint at level 1 and mesh shades open, 2. Tint at level 2 and mesh shades open, 3. Tint at level 2 with mesh shades closed, 4. Tint at level 4 with mesh shades open.

Sensor Sampling Interval Changes and Communication Issues

As noted in Table 2, sensor sampling intervals were increased following the Multi-IEQ study due to increased confidence in the ability of the sensors to sample frequently without requiring frequent battery changes. Following the Multi-IEQ study, illuminance and CCT/illuminance sensors with wall outlet power supplies were purchased such that sample rates for desk-level lighting sensors could be increased to 1 min/sample, while battery powered light sensors deployed at the window-level remained at a sampling rate of 10 min/sample. While some bias may be introduced by altering sampling frequency, increasing data sampling rate improved our ability to detect morning peaks in illuminance during sunrise, the most important time of day for glare control due to these office modules having a large east-facing façade.

Poor sensor communication led to 4 sensors being removed from the data set during the Multi-IEQ Study, and prior to the latter studies steps were taken to improve the lab's ability to detect and respond to sensor failures. Field gateways were moved closer to the experimental modules to reduce signal pathlength and sensors were installed and operated for multiple weeks prior to study start to check for connection and bias issues. Additionally, emailed data collection reports and improved real-time visualizations provided the ability to quickly detect and respond to sensor failures. In the event of a sensor failure, sensors were replaced at the end of the day after all participants left the office so as not to draw attention to the presence of the sensors and to limit experimenter interactions with participants in the aim of maintaining as normal of an office environment as possible.

Façade Control

Figure S15 describes the overall trends in how the façades were controlled during the Daylighting Study. When mesh shades were controlled by occupants they were set to 50-90% open, except for window W02 which was frequently fully closed. Automated tint levels increased from level 1-2 at 06:00 to level 3-4 at 10:00 and then decreased back to level 1 by 12:00 along the east façade, while north façade windows tinted to level 2-3 during the first three hours of the workday, returning to level 1 by 09:00. Automated tinting of four windows were overridden by occupants (Figure S13d), with W02 often being set to the darkest tint (level 4) and W06 being set to the lowest tint state (level 1). Shade height data collection errors occurred during the first six weeks of the Multi-IEQ study, but data collected during weeks 7-18 during the Near-Optimal, Optimal, Mixed 1, and Mixed 2 show participants on average kept windows more open (90% open on average) than during the Mesh Shades condition of the Daylighting Study (70% open). Minimum shade height was also different between the two studies, with W02 in the Mesh Shades condition averaging 5% open versus W07/W08 averaging 67% open during the Multi-IEQ Study. Additional details and statistical summaries of shade and tint control during the Daylighting study are included in Jamrozik et al., 2019.

During the Mesh Shades and Dynamic Tint conditions, differences in window-level façade control driven by occupant control patterns resulted in increased spatial variability in amount of natural light at each desk, with desks near windows that were controlled to reduce natural light (W02, D01-03) measuring lower desk-level illuminance while windows controlled to increase natural light, e.g. by overriding dark tint to lighter tint states at W06, resulted in increased amounts of natural light at adjacent desks (D05-07). Additionally, desks near pillars between windows also received less natural light than desks placed near centers of windows. However, compared to the Multi-IEQ study, between-desk natural light differences were greatly reduced for the Daylighting study by altering the desk layout.

To explore the relationships between façade control, desk-level lighting conditions, and desk-level air temperature, hourly medians of data collected during the Mesh Shades and Dynamic Tint conditions from the Daylighting Study were compared on a by-desk basis, as shown in Figure S16-S18 for D03, D06, and D09, respectively, desks chosen as representative of typical conditions experienced at a desks with a range of shade heights (55-100% open) and without automated tint level of the adjacent window being overridden. To evaluate linear relationships between desk-illuminance and temperature, shade height data were split between hours with nearly fully open shades (>90% open) and hours with partially or fully closed shades (<90% open). Tint level data were split between low tint levels (1 and 2) and dark tint levels (3 and 4). Quantile regressions (50th percentile) were fit for all data and each subset of data during the two experimental conditions, shown as a green line (all data), blue line (>90% open/low tint level), or red line (<90% open/high tint level). Quantile regression was used to limit the impact of extreme illuminance values on derived relationships.

Most desks showed no difference in linear relationships between subsets of data during the Mesh Shades condition, demonstrating minimal to no impact of partially lowering shades on reducing desk temperatures (Figures S16b-18b). Tint state, however, did significantly alter the relationship between desk temperature and illuminance (Figures 16f-18f), greatly reducing temperature variability over a range of illuminance levels at darker tint levels (>2). The hourly component of these comparisons of variability is also important, as Figures S16a-18a, S16c-18c, S16e-18e, and S16g-18g demonstrate, because between the two experimental conditions there are differences in when peak desk-level illuminance and temperature occur.

Table S1. Specifications of wireless and reference-grade sensors used in continuous monitoring and spatial assessments during the three office studies.

Manufacturer/Model	Metric	Sensor Type/Class	Data Units	Accuracy
Ventilation System Sensors				
Ebtron GTx116-P+ (AHU)	Air Flow	Pressure Differential	CFM	±3%
Price SP300 (VAV)	Air Flow	Pressure Differential	CFM	≤±5%
BAPI BA/BS2-WT-S	Air Temperature	Thermostat	°C	±0.3 °C
Wireless Sensors				
Monnit Humidity Sensor	Air Temperature	Thermistor	°C	±1 °C
	RH	Resistive	%RH	±3%
Monnit Temperature Sensor	Air Temperature	Thermistor	°C	±1 °C
Wovyn Lux1000 Sensor	Illuminance	Photodiode	lx	NA
Wovyn ColorLux1000 Sensor	Illuminance	Photodiode	lx	NA
	CCT	RGB Photodiodes	K	NA
Wovyn Air Quality Monitor	CO_2	NDIR (Winsen MH-Z16)	ppm	±(50 ppm + 5%)
Reference Instruments				
TSI Q-Trak Probe 964	Air Temperature	Thermistor	°C	±0.3 °C
	RH	Capacitive	%RH	±3 %RH
Konica Minolta CL-500A	Illuminance	Class AA Illuminance Meter	lx	±2%
	CCT	(JIS C 1609-1)	K	xy: ±0.0015
NTi XL2 Sound Level Meter	Sound Level	Class 1 Microphone	dBA	±3 dB (sensitivity)
	Audio Spectrum	(IEC61672, ANSI S1.4)		

Table S2. Arithmetic mean, GSD, maximum, and minimum from environmental monitoring during the Multi-IEQ Study.

Multi-IEQ Study

Environmental Measurement	**Near-Optimal (Baseline)**	**Optimal**	**Sub-Optimal 1**	**Mixed 1**	**Sub-Optimal 2**	**Mixed 2**
(Sensor No., Units)	Arith. Mean, GSD (Max/Min)					
AHU Air Flow	1017, 1.3	983, 1.3	1,055, 1.0	812, 1.5	1,035, 1.1	818, 1.4
(N=1, CFM)	(1,332/0)	(1,255/125)	(1,205/697)	(1,171/226)	(1,089/701)	(1,087/403)
VAV Air Flow	371, 1.4	356, 1.5	393, 1.2	288, 1.8	403, 1.2	243, 1.7
(N=3, CFM)	(466/0)	(469/0)	(468/54)	(525/28)	(465/104)	(458/65)
AHU Return RH	44, 1.1	46, 1.1	48, 1.1	44, 1.1	48, 1.1	44, 1.1
(N=1, %RH)	(57/0)	(66/28)	(52/30)	(60/30)	(61/30)	(52/30)
Thermostat Temp.	22.5, 1.0	22.0, 1.0	20.6, 1.0	23.7, 1.0	20.9, 1.1	23.4, 1.0
(N=3, °C)	(25.0/20.0)	(26.7/18.3)	(26.7/18.3)	(26.7/18.3)	(28.9/18.9)	(28.9/18.3)
Desktop Temp.	24.1, 1.1	23.5, 1.1	22.1, 1.1	25.5, 1.1	22.0, 1.1	25.1, 1.1
(N=8, °C)	(29.1/20.5)	(28.7/20.5)	(26.0/18.7)	(30.7/19.5)	(26.0/18.7)	(29.3/18.7)
Window Temp.	23.6, 1.1	22.5, 1.1	24.6, 1.2	24.8, 1.1	22.4, 1.1	24.2, 1.1
(N=3, °C)	(30.4/18.8)	(29.2/18.1)	(36.8/18.2)	(31.6/18.4)	(30.3/16.7)	(27.9/19.0)
Wearable Air Temp.	30.4, 1.1	29.7, 1.1	29.2, 1.1	31.1, 1.1	29.0, 1.1	31.0, 1.0
(N=8, °C)	(34.4/23.9)	(33.9/20.6)	(33.9/19.4)	(35.6/23.9)	(33.3/22.8)	(34.4/24.4)
Wearable Skin Temp.	31.6, 1.0	31.2, 1.0	30.5, 1.0	32.3, 1.0	30.7, 1.0	32.2, 1.0
(N=8, °C)	(35.0/25.0)	(34.4/23.9)	(35.0/26.1)	(35.0/26.1)	(33.9/25.6)	(35.0/27.2)
Desktop RH	41.4, 1.1	44.3, 1.2	48.5, 1.1	38.3, 1.1	48.6, 1.1	40.5, 1.1
(N=8, %)	(55.4/31.5)	(60.8/24.0)	(56.3/37.5)	(52.5/29.7)	(66.9/35.5)	(55.4/30.6)
Desktop Illuminance	586, 2.5	438, 2.6	265, 2.6	562, 2.5	423, 3.0	530, 2.6
(N=9, lx)	(6,441/23)	(2,740/3)	(1,775/51)	(6,416/1)	(1,665/20)	(3,949/19)
Window Illuminance	5,919, 3.8	1,265, 5.3	608, 6.6	5,181, 4.1	53, 3.3	1,349, 6.0
(N=7, lx)	(54,542/0)	(46,986/0)	(30,760/0)	(53,263/0)	(2,653/0)	(26,896/0)
Wearable Illuminance	227, 6.5	132, 5.9	67, 3.4	203, 5.5	67, 3.6	145, 4.9
(N=8, lx)	(21,949/0)	(9,949/0)	(1,442/0)	(34,013/0)	(1,488/0)	(6,529/0)
Near-Desk CO_2	516, 1.1	515, 1.1	518, 1.1	535, 1.1	510, 1.1	537, 1.1
(N=4, ppm)	(986/366)	(974/351)	(768/374)	(809/377)	(856/368)	(743/377)
Background CO_2	491, 1.2	487, 1.1	517, 1.1	520, 1.1	482, 1.1	507, 1.1
(N=2, ppm)	(944/71*)	(863/198*)	(696/388)	(711/386)	(813/376)	(721/378)
External CO_2	472, 1.1	484, 1.1	469, 1.1	459, 1.1	475, 1.1	474, 1.1
(N=1, ppm)	(812/335*)	(837/367)	(779/373)	(744/355)	(695/371)	(599/363)
Desktop Sound Level	48.2, 2.1	47.7, 2.1	48.1, 2.1	47.6, 2.0	48.0, 1.8	47.3, 2.1
(N=1, dBA)	(57.8/40.0)	(58.8/38.1)	(58.4/40.4)	(57.3/41.0)	(56.2/42.1)	(55.1/38.8)

* Minimum CO_2 values impacted by sensor noise at low values, fixed after first two weeks of study.

Table S3. Arithmetic mean, GSD, maximum, and minimum from environmental monitoring during the Daylighting and Electric Lighting studies.

Daylighting Study				*Electric Lighting Study*		
Environmental Measurement	**No View (Baseline)**	**Mesh Shades**	**Dynamic Tint**	**Experimental Condition**	**Fluorescent (Baseline)**	**LED**
(Sensor No., Units)	Arith. Mean, GSD (Max/Min)			(Sensor No., Units)	Arith. Mean, GSD (Max/Min)	
AHU Air Flow (N=1, CFM)	511, 1.4 (1,200/258)	667, 1.5 (1,385/283)	706,1.7 (1559/2)	-	-	-
VAV Air Flow (N=3, CFM)	225, 1.9 (467/0)	261, 2.0 (472/0)	238, 2.1 (600/0)	VAV Air Flow (N=2, CFM)	146, 1.5 (384/77)	110, 1.3 (329/76)
Thermostat Temp. (N=3, °C)	23.3, 1.0 (24.4/21.1)	23.6, 1.0 (25.6/22.2)	23.6, 1.0 (26.1/22.2)	Thermostat Temp. (N=2, °C)	22.3, 1.0 (23.3/21.7)	22.0, 1.0 (22.8/21.7)
Desktop Temp. (N=10, °C)	23.9, 1.0 (27.4/19.9)	24.6, 1.1 (31.1/22.0)	24.7, 1.0 (34.6/21.9)	Desktop Temp. (N=4, °C)	22.4, 1.0 (23.8/21.1)	22.0, 1.0 (23.7/20.8)
Window Temp. (N=8, °C)	25.9, 1.2 (43.3/16.5)	26.1, 1.2 (40.9/18.1)	26.8, 1.1 (43.4/19.6)	-	-	-
Wall Temp. (N=8, °C)	23.2, 1.0 (26.3/19.5)	23.8, 1.1 (29.5/21.4)	24.0, 1.0 (29.5/21.5)	Wall Temp. (N=7, °C)	22.3, 1.0 (24.1/17.8)	21.5, 1.1 (24.1/17.2)
Desktop RH (N=10, %)	39.7, 1.1 (50.1/29.3)	37.7, 1.1 (48.4/26.6)	37.8, 1.1 (47.4/24.1)	Desktop RH (N=4, %)	41.9, 1.0 (44.8/38.5)	42.4, 1.0 (46.6/35.9)
Desktop Illum. (N=10, lx)	295, 1.2 (459/0)	545, 1.6 (7,737/0)	519, 1.5 (11,271/0)	Desktop Illum. (N=10, lx)	248, 1.5 (486/0)	322, 1.6 (642/0)
Desktop Illum. (CCT sensors, N=10, lx)	293, 1.1 (412/44)	1,186, 2.2 (32,734/1)	954, 1.9 (39,828/108)	Desktop Illum. (CCT sensors, N=10, lx)	293, 1.3 (524/41)	315, 1.4 (630/0)
Window Illum. (N=16, lx)	60, 3.6 (763/0)	3,393, 5.2 (38,010/0)	2,072, 4.2 (59,580/0)	-	-	-
Window Illum. (CCT sensors, N=8, lx)	54, 3.8 (38,782/0)	4,184, 4.9 (31,642/0)	2,511, 4.5 (27,613/3)	-	-	-
Desktop CCT (N=10, K)	4291, 1.0 (6183/3871)	4805, 1.1 (19,237/625)	5,255, 1.1* (18,963/625)	Desktop CCT (N=10, K)	3,531, 1.1 (6,154/2,858)	5,970, 1.0 (7,047/1,243)
Window CCT (N=8, K)	10,822, 1.9* (19,965/0)	5,593, 1.2 (16,213/2,852)	6,733, 1.4* (18,580/274)	-	-	-

* Desk and window CCT sensors responded erratically at darker tint levels, 3 and 4, impacting all data in the No View condition (level 4) and data collected during morning periods of the Dynamic Tint condition. Desk-level sensors were less impacted than window-level sensors.

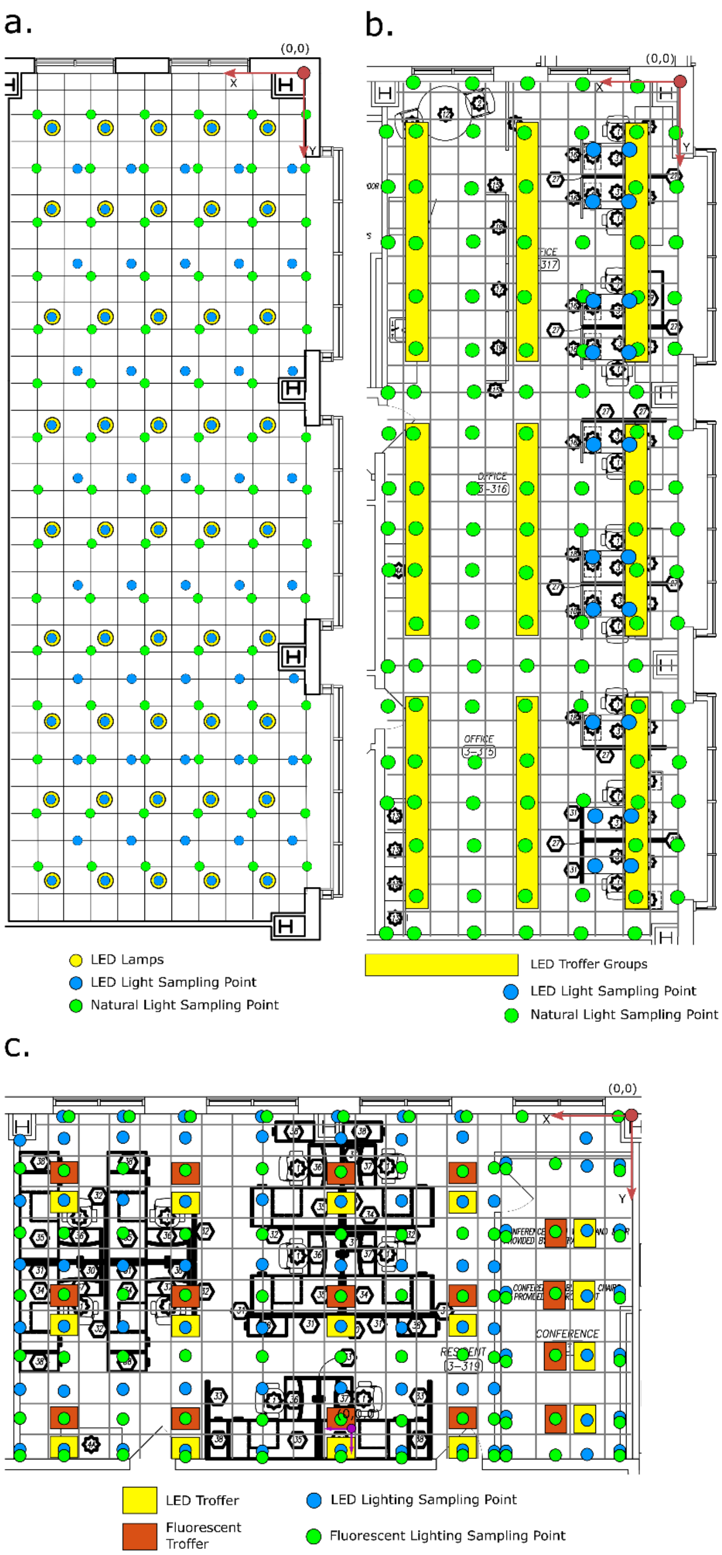


Figure S1. (a) LED lighting design and sample points for electrical light (blue) and natural light (green) spatial lighting analysis during the Multi-IEQ Study. (b) LED troffer design and sample points for electrical lighting (blue) and natural lighting (green) spatial lighting analysis during the Daylighting Study. (c) Lighting design and sample points for LED lighting (blue) and fluorescent lighting (green) spatial lighting analysis during the Electrical Lighting Study. Note: X- and Y-axes used later for plotting are labeled, with the origin (0,0) located at the northeast corner of the offices.

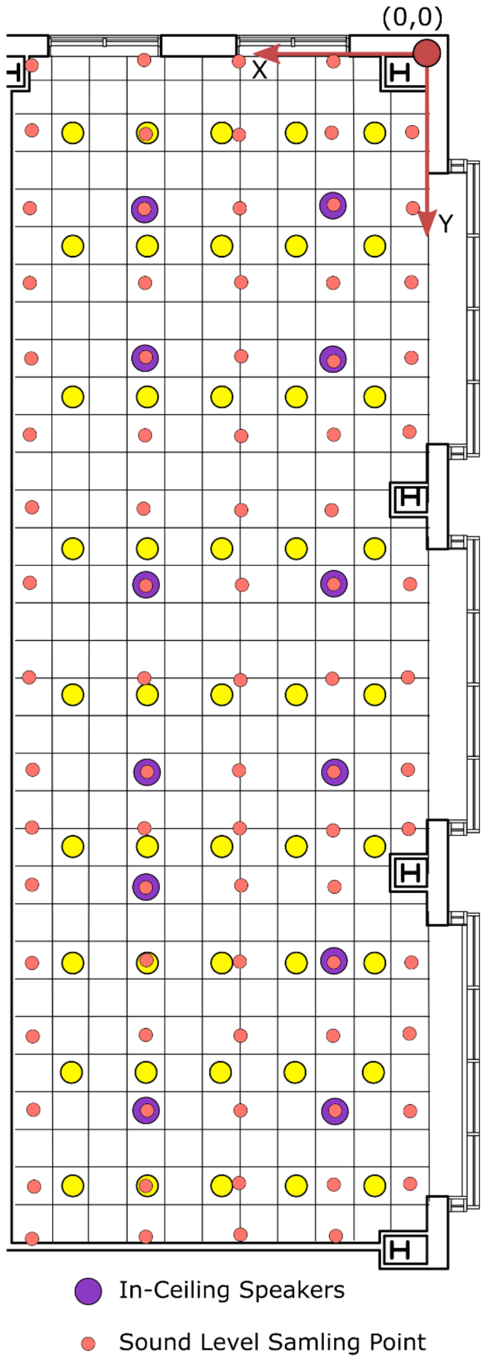


Figure S2. Speaker locations and sample points for spatial sound analysis. Note: X- and Y-axes used later for plotting are labeled, with the origin (0,0) located at the northeast corner of the office.

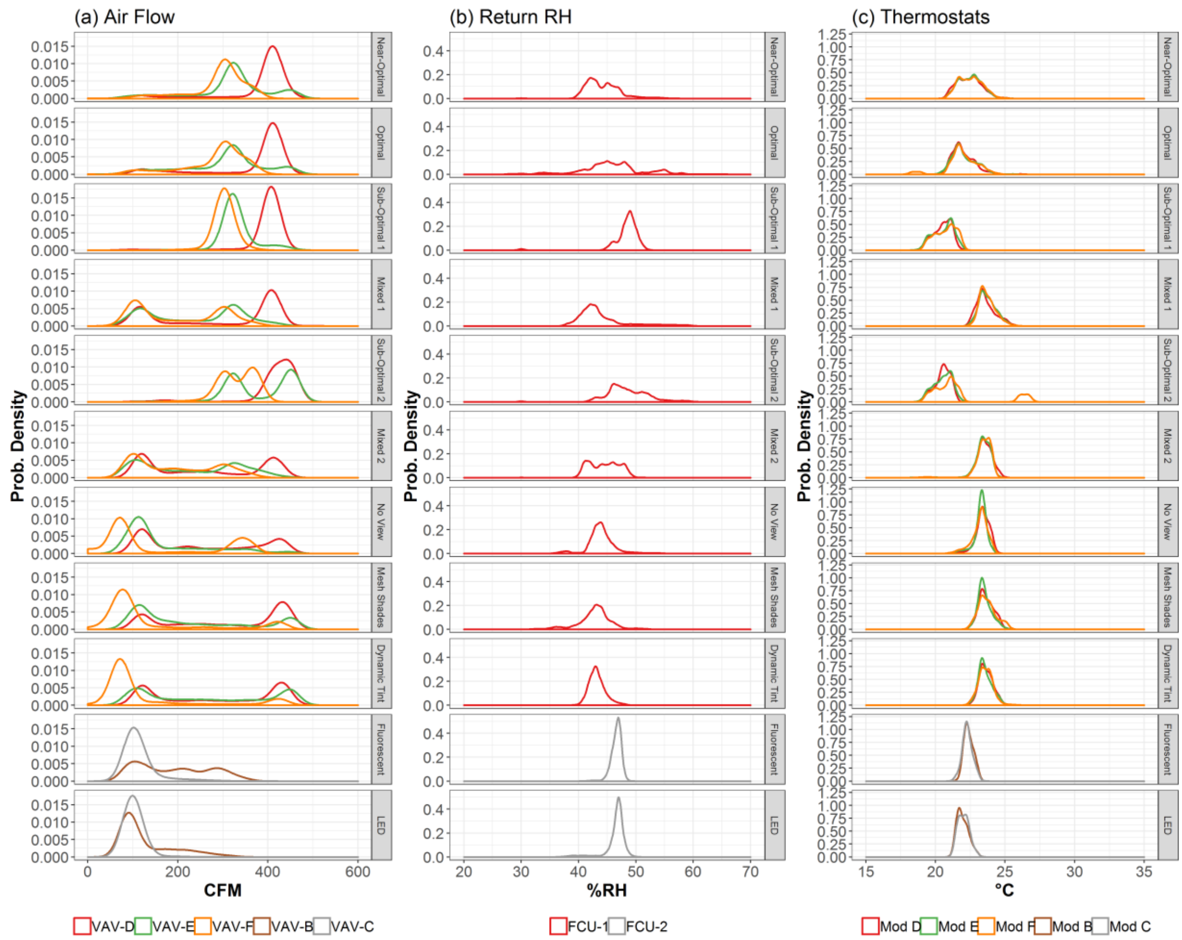


Figure S3. Distribution of HVAC operational conditions during each experimental condition of three office experiments: (a) VAV air flow rate (CFM), (b) return air RH (%RH), (c) thermostat temperature (°C).

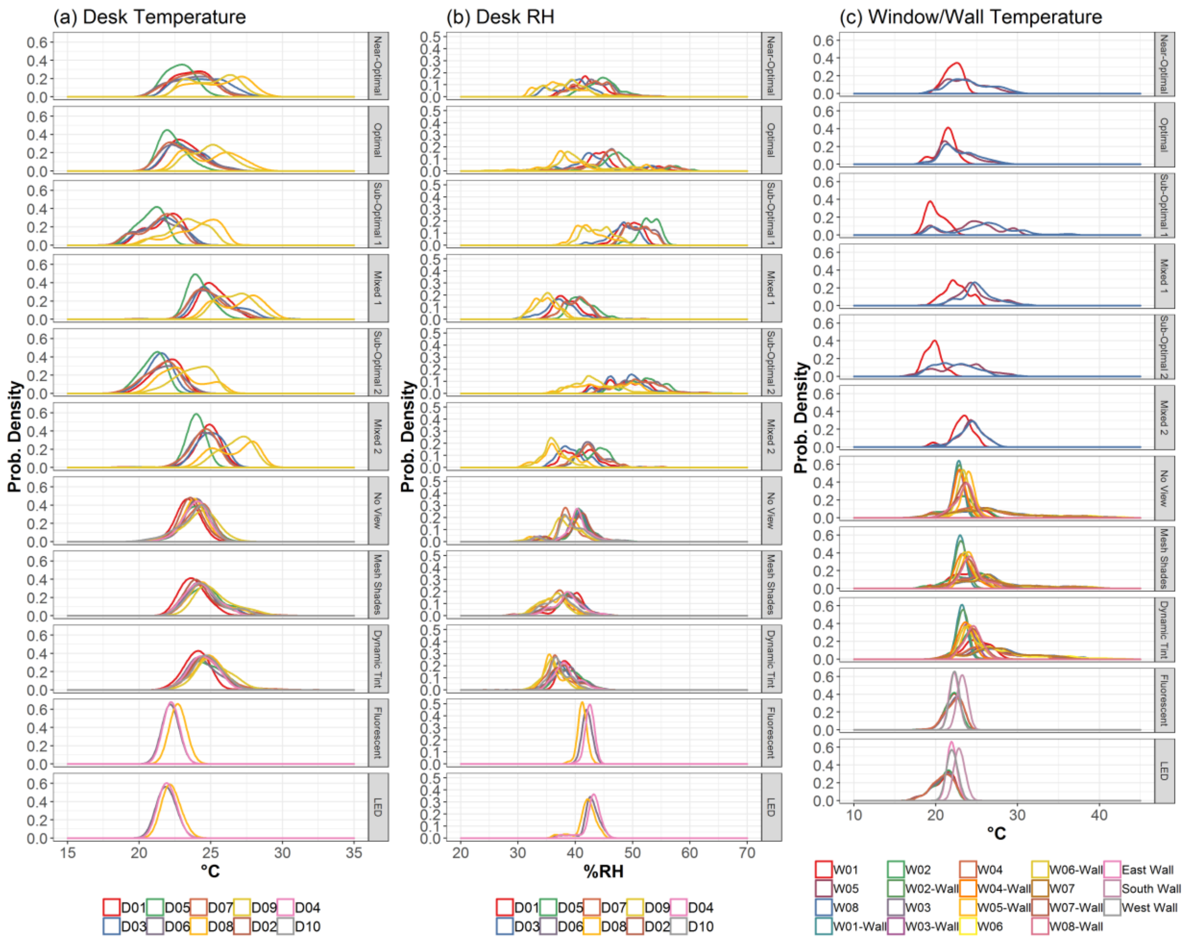


Figure S4. Distribution of thermal conditions during each experimental condition of three office experiments: (a) desk temperature (°C), (b) desk RH (%RH), (c) window/wall temperature (°C).

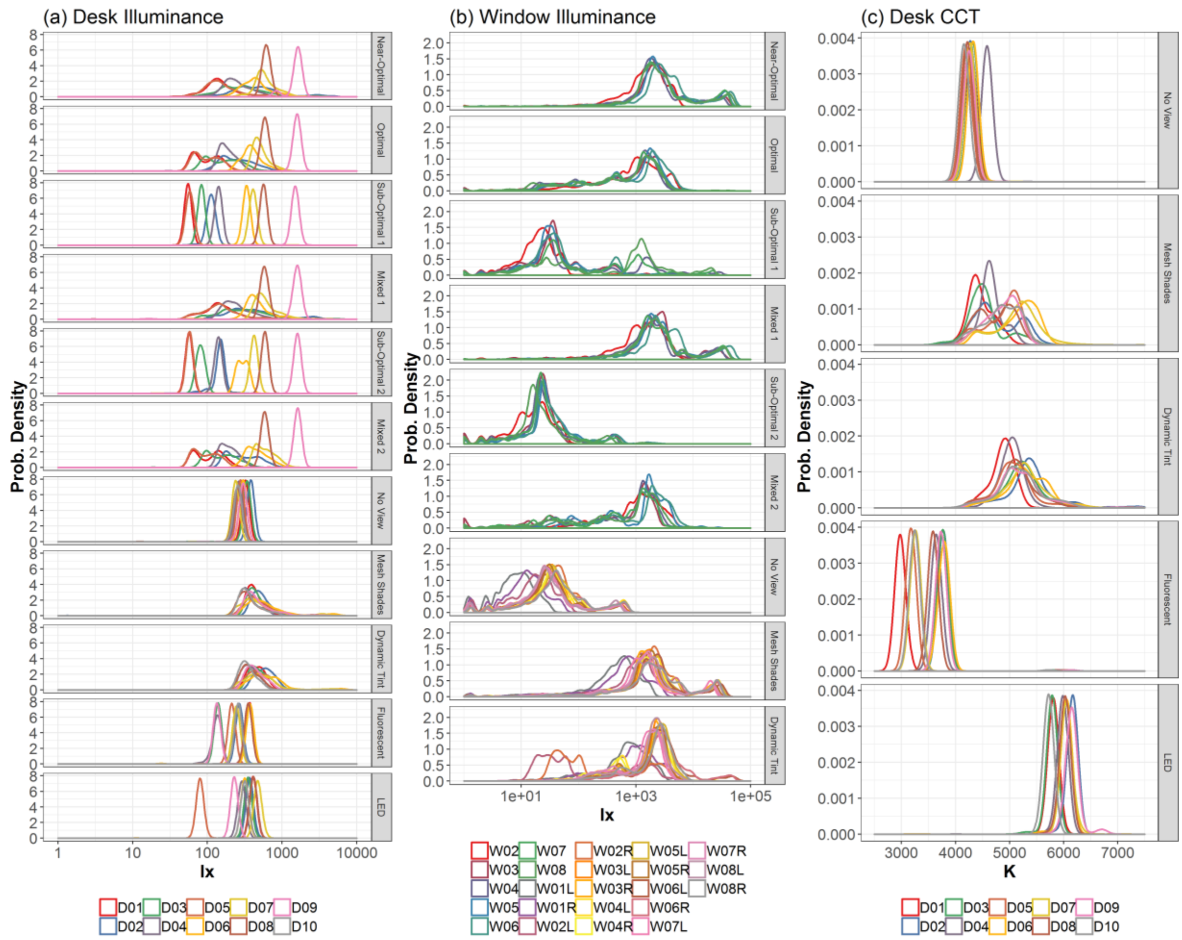


Figure S5. Distribution of lighting conditions during each experimental condition of three office experiments: (a) desk illuminance (lx), (b) window illuminance (lx, no data from Electric Lighting Study), and (c) desk CCT (K, no data from Multi-IEQ Study).

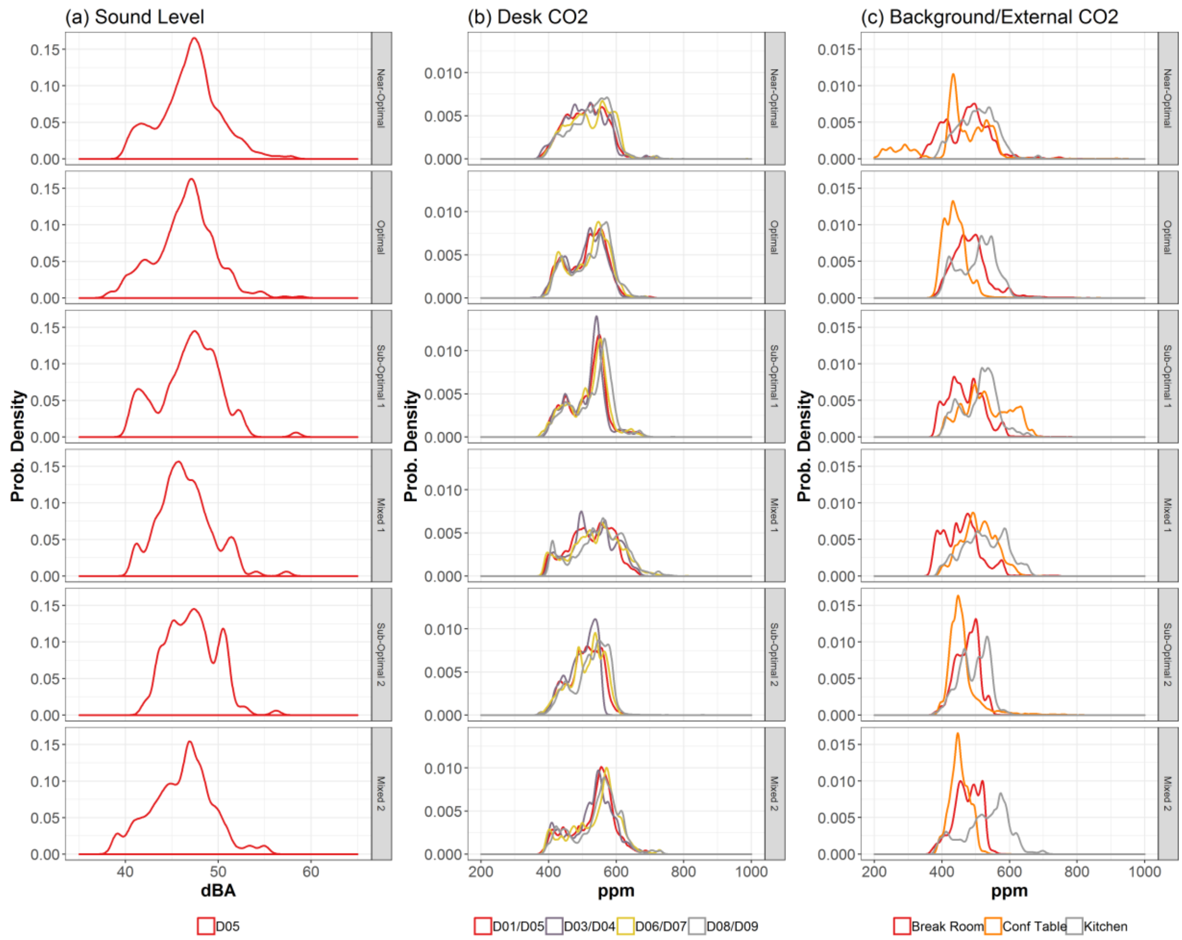
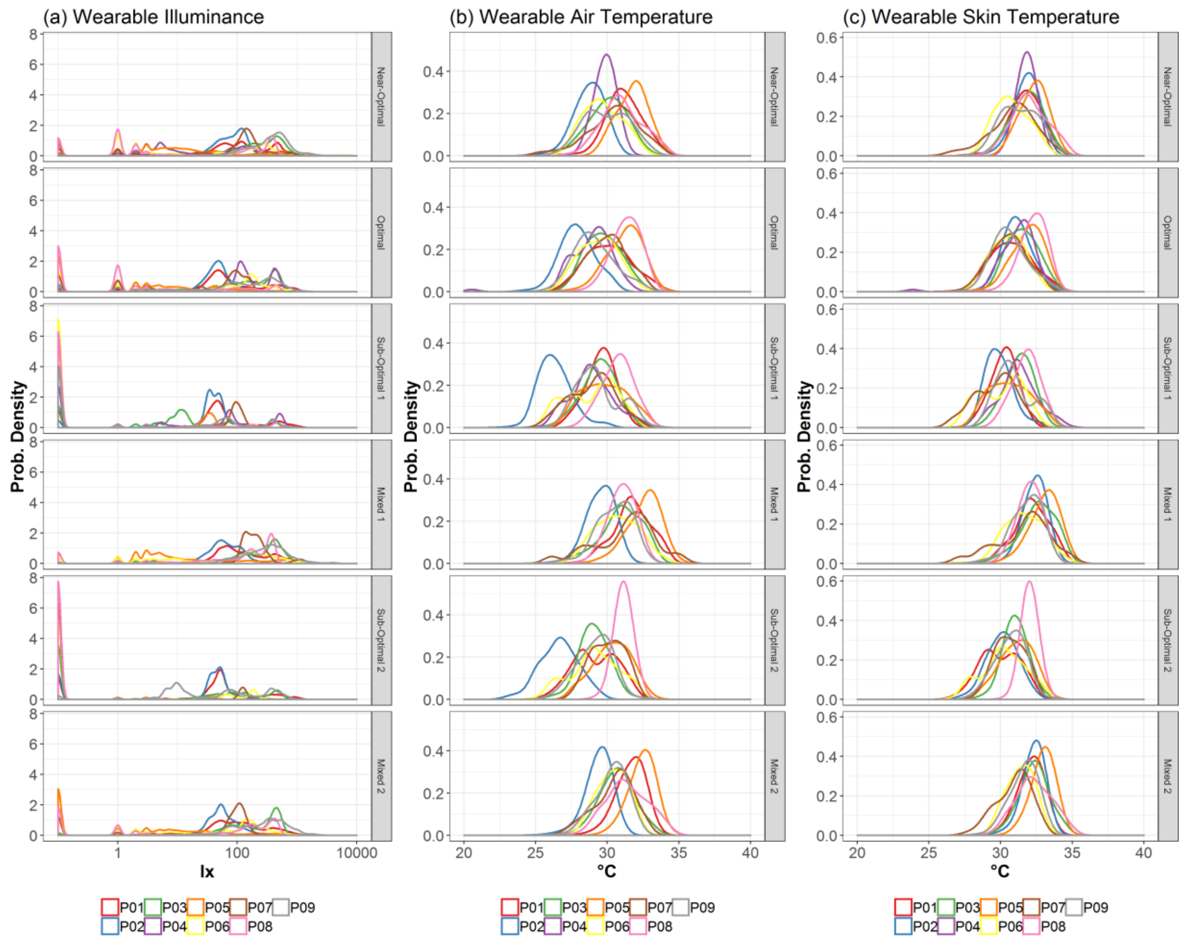


Figure S6. Distribution of sound levels and CO_2 concentrations during each condition of the Multi-IEQ Study: (a) sound levels (dBA), (b) desk-level CO_2 concentrations (ppm), and (c) background and external CO_2 concentrations (ppm).

140 

141 **Figure S7.** Distribution of wearable-based environmental data during each condition of the Multi-
142 IEQ Study: (a) illuminance (lx), (b) air temperature (°C), and (c) skin temperature (°C).

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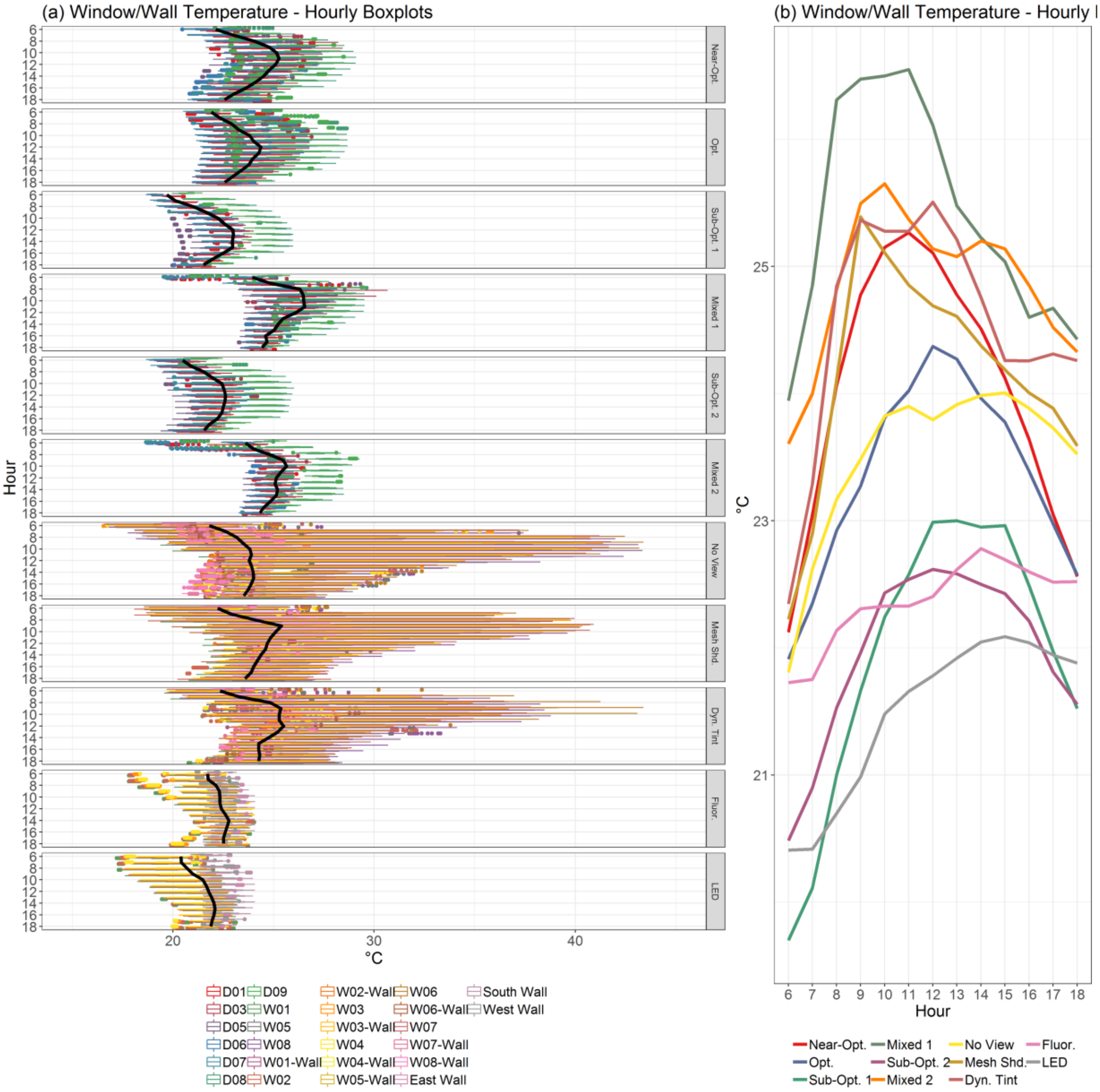

Figure S8. (a) Hourly boxplots plots by sensor and (b) hourly medians by experimental condition of window and wall temperatures (°C) during the three office experiments.

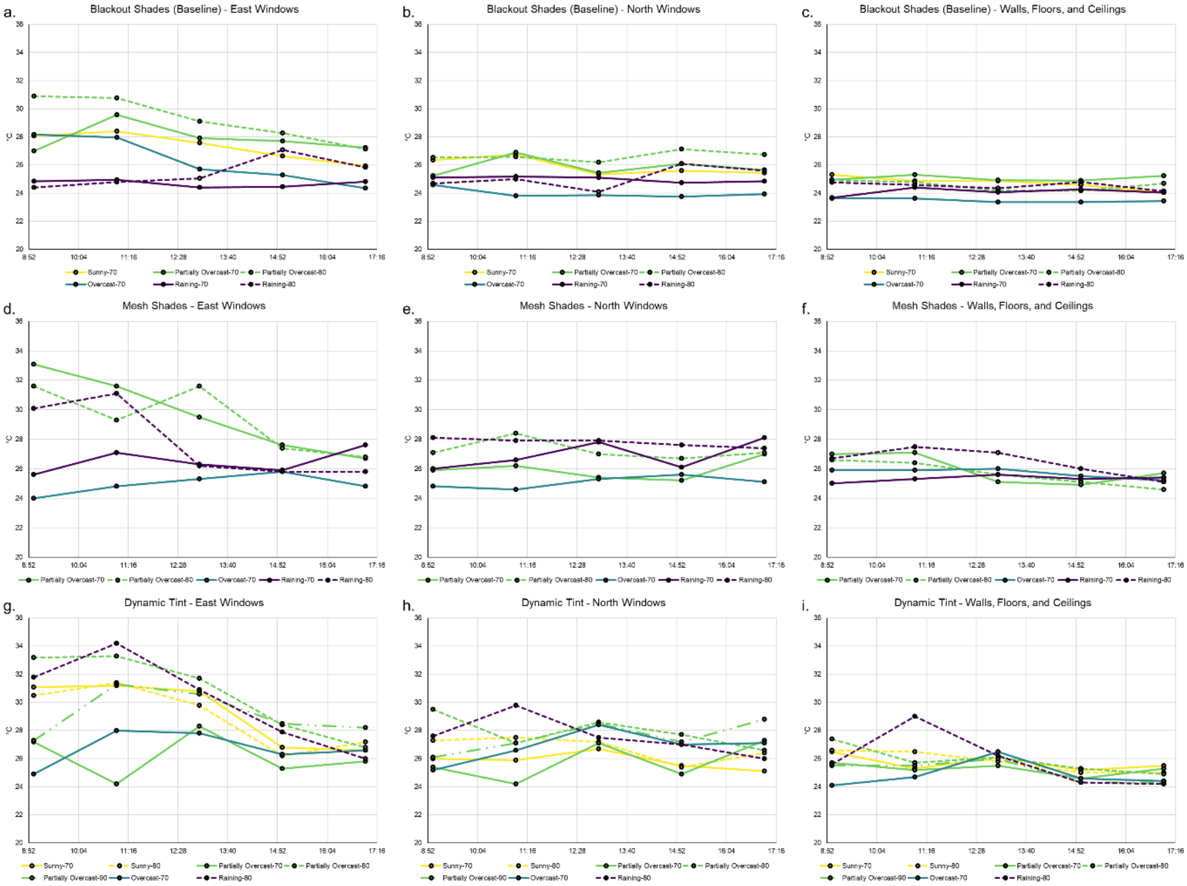

Figure S9. Average surface temperature by hour of day for east windows (left column), north windows (center column), and walls, ceilings, and floors (right column) for the (a, b, c) no view ("Blackout Shades") condition, (d, e, f) mesh shade condition, and (g, h, i) dynamic tint conditions during the Daylighting Study.

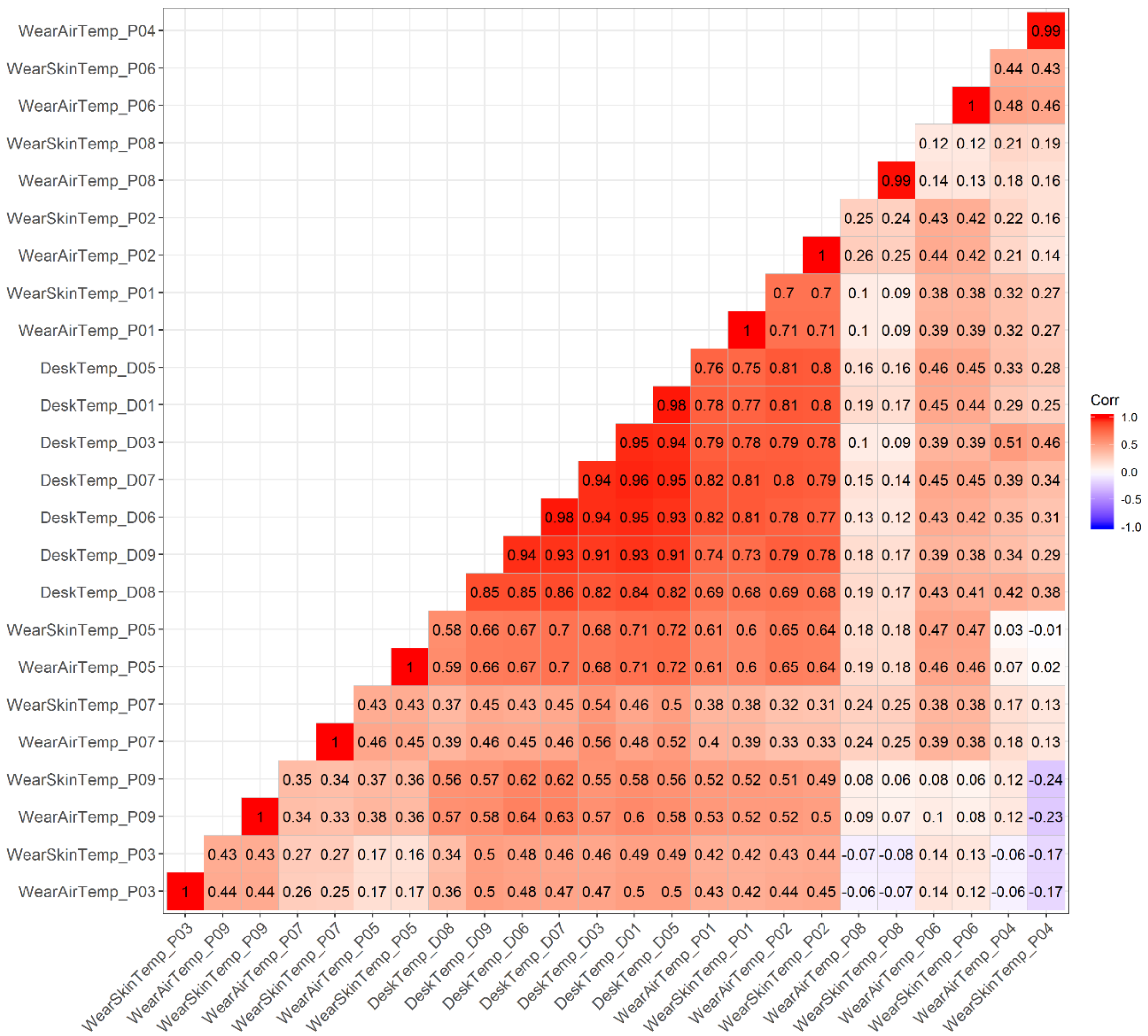

Figure S10. Correlation matrix ordered by hierarchical cluster for desk-level (DeskTemp_D0#) and wearable temperature (WearAirTemp_P0# and WearSkinTemp_P0#) hourly geometric means during the Multi-IEQ Study.

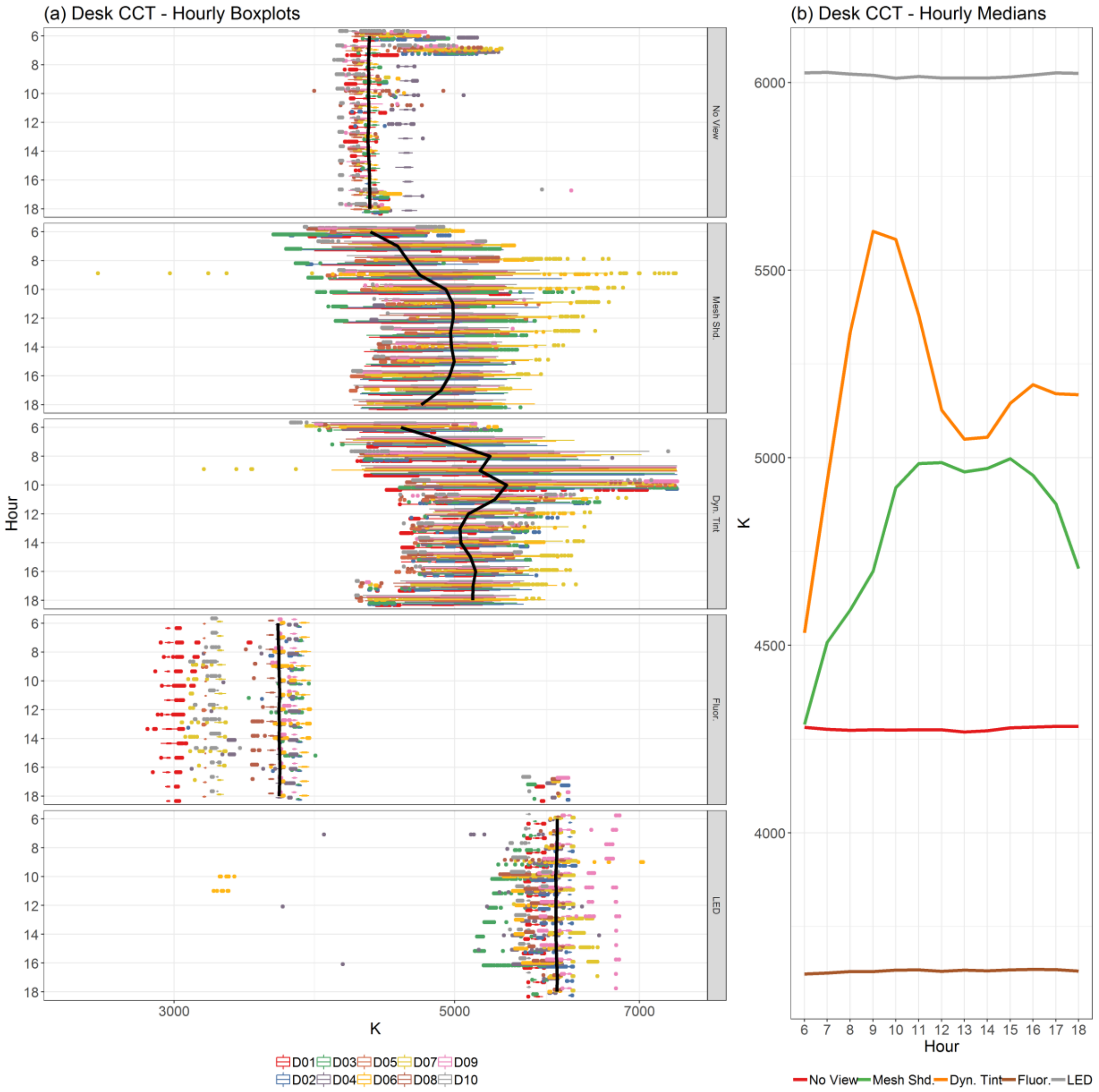

Figure S11. (a) Hourly boxplots plots by sensor and (b) hourly medians by experimental condition of desk CCT (K) during the Daylighting and Electric Lighting Studies.

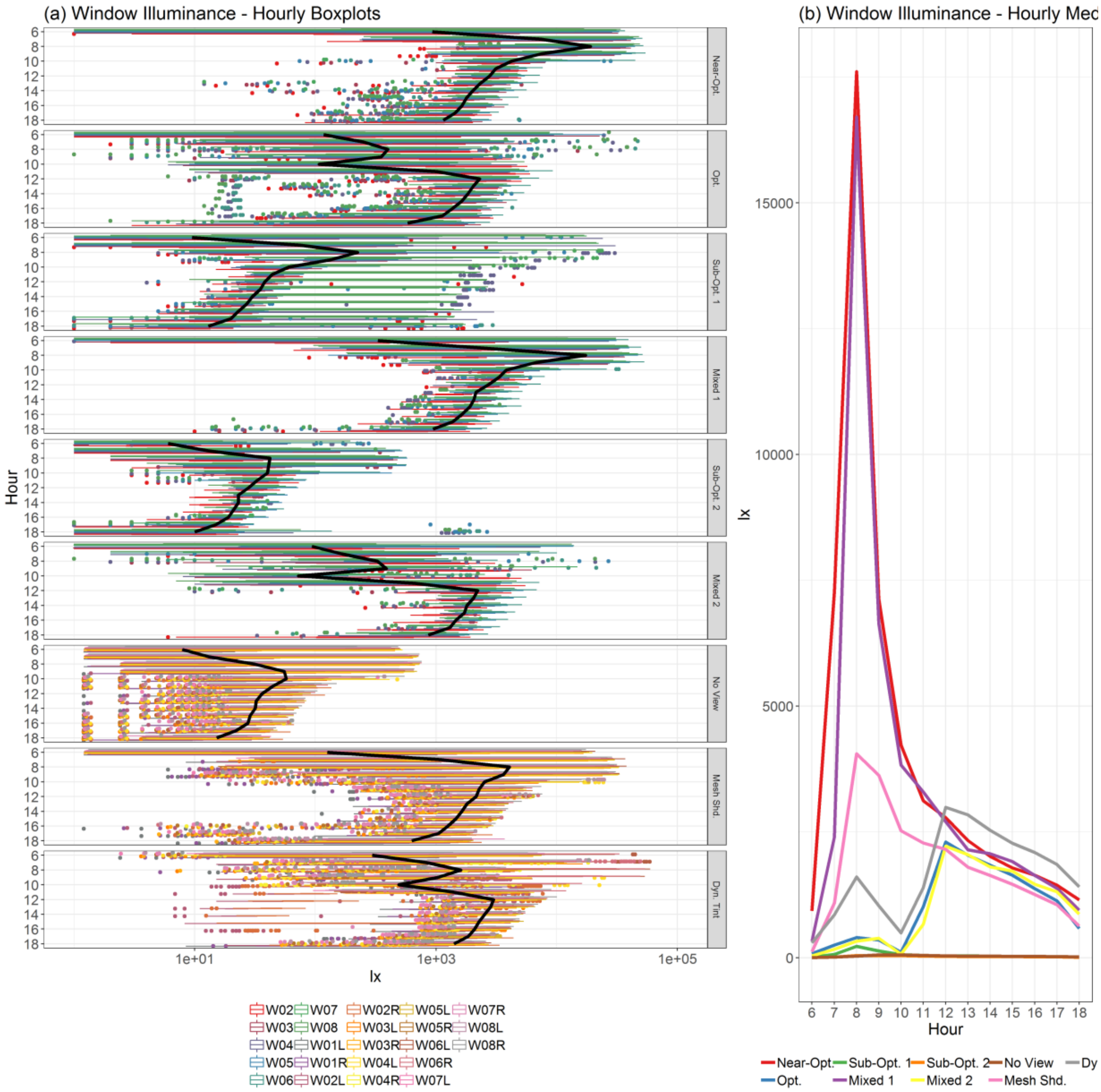

Figure S12. (a) Hourly boxplots plots by sensor and (b) hourly medians by experimental condition of window illuminance (lx) during the Multi-IEQ and Daylighting Studies.

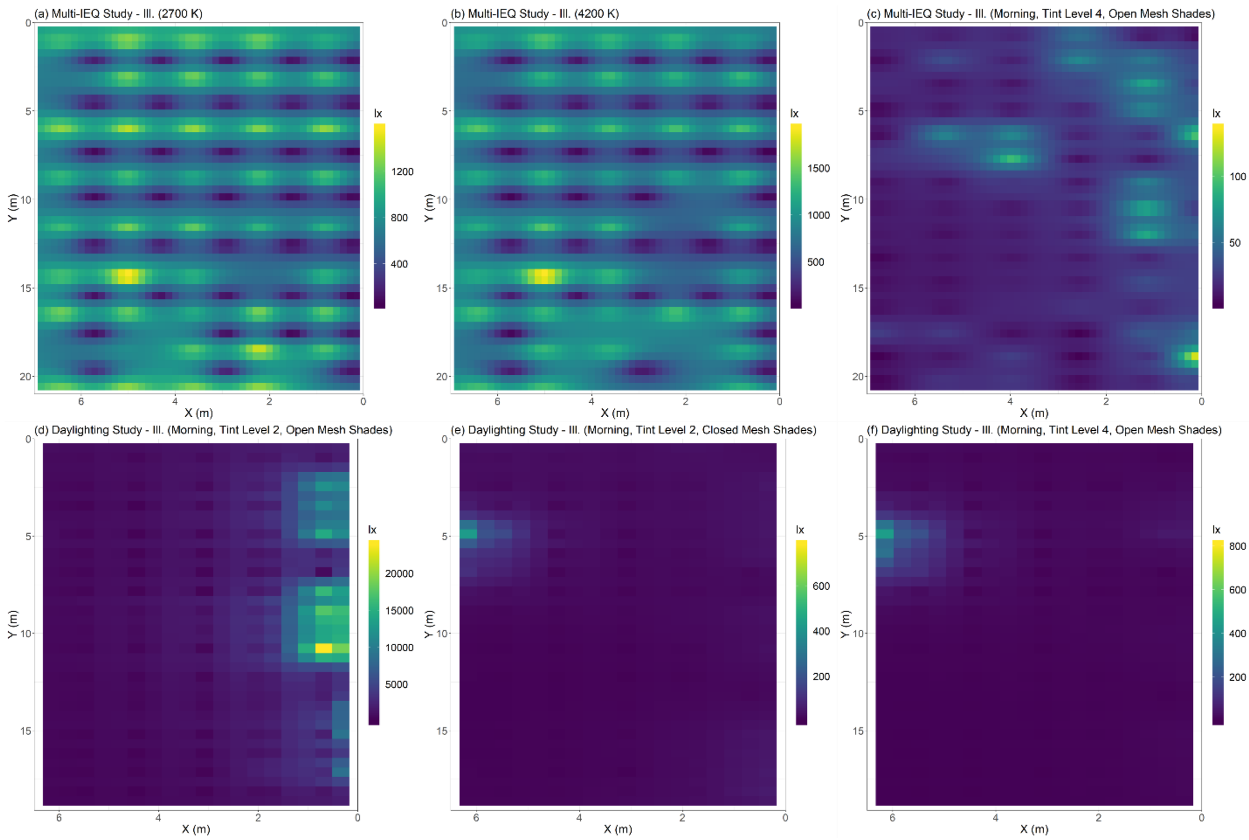

Figure S13. Spatial horizontal illuminance (lx) variability during the Multi-IEQ Study of electric lighting at (a) 2700 K and (b) 4200 K and of (c) natural light during morning at tint level 4 with mesh shades open. Spatial horizontal illuminance (lx) variability during the Daylighting Study of (d) natural light during morning at tint level 2 with mesh shades open, (e) natural light during morning at tint level 2 with mesh shades closed, and (f) natural light during morning at tint level 4 with mesh shades open. Note: Natural lighting assessments during the Daylighting Study used a small undercabinet light for visibility during low light testing conditions (mesh shades closed and tint level 4), which is evident in these results.

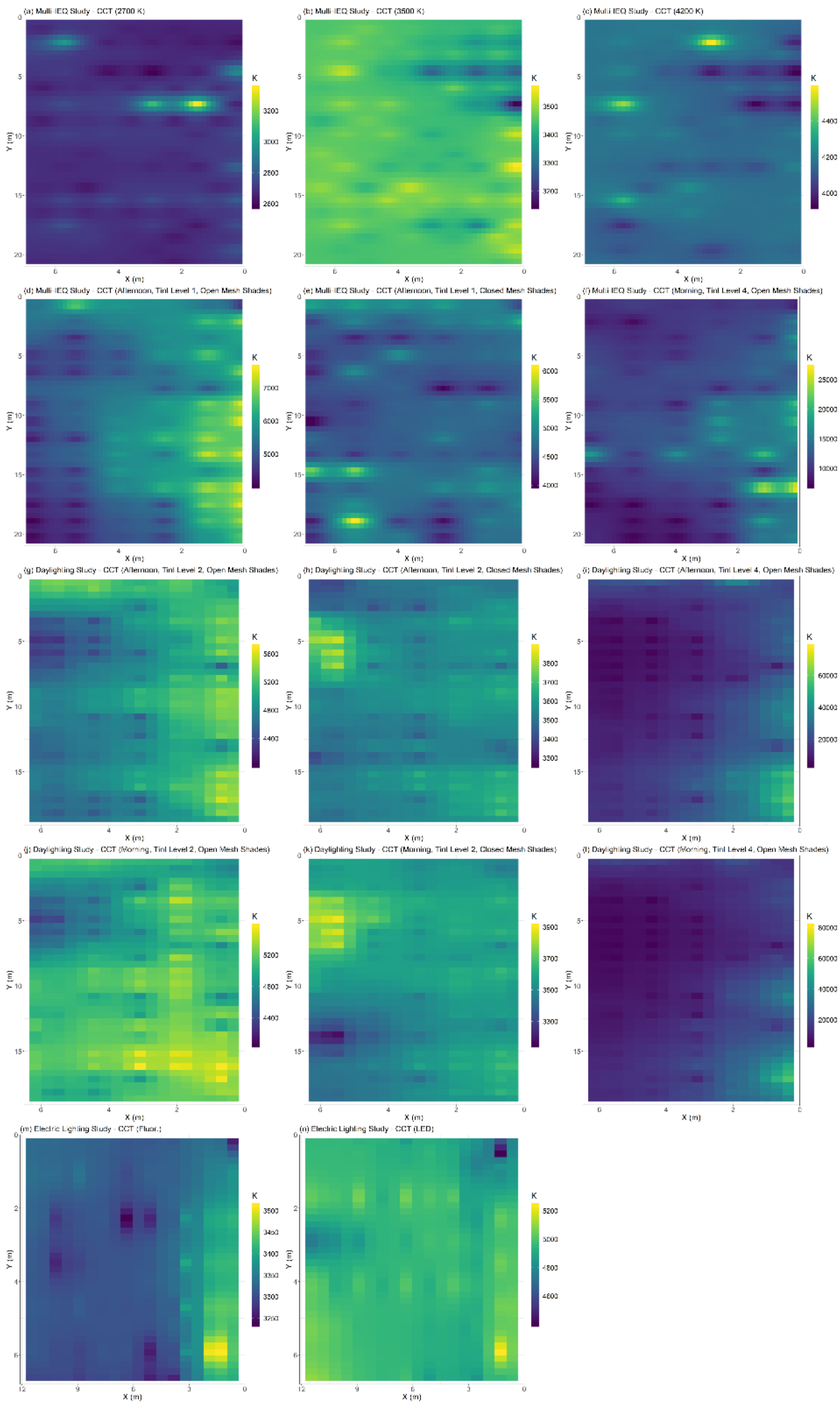

Figure S14. Spatial horizontal CCT (K) variability during the Multi-IEQ study of electric lighting at (a) 2700 K, (b) 3500 K, and (c) 4200 K and of natural light during (d) afternoon at tint level 1 with mesh shades open, (e) afternoon at tint level 1 with mesh shades closed, and (f) morning at tint level 4 with mesh shades open. Spatial horizontal CCT (K) variability during the Daylighting study of natural light during (g) afternoon at tint level 2 with mesh shades open, (h) afternoon at tint level 2 with mesh shades closed, (i) afternoon at tint level 4 with mesh shades open, (j) morning at tint level 2 with mesh shades open, (k) morning at tint level 2 with mesh shades closed, and (l) morning at tint level 4 with mesh shades open. Spatial horizontal CCT (K) variability during the Electric Lighting Study with (m) fluorescent lighting and (n) LED lighting. Note: Natural lighting assessments during the Daylighting Study used a small undercabinet light for visibility during low light testing conditions (mesh shades closed and tint level 4).

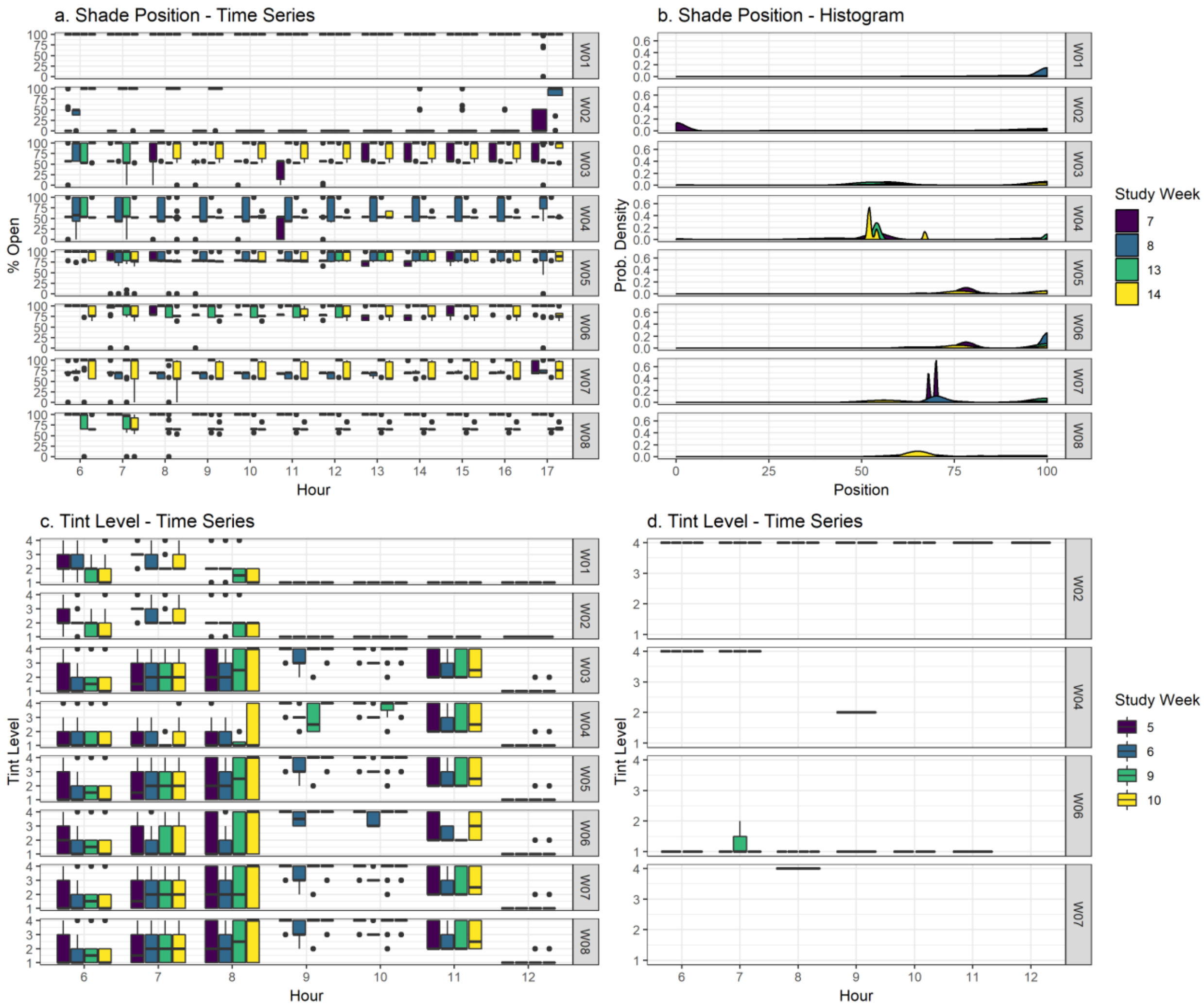

Figure S15. Summaries of shade position and tint state during work hours (6:00-18:00) on weeks of Mesh Shade conditions (a,b) and Dynamic Tint conditions (c,d): (a) Boxplots of shade position by week, (b) probability density of position by window and week, (c) boxplots of automated tint state by week, (d) boxplot of override tint state by window and week.

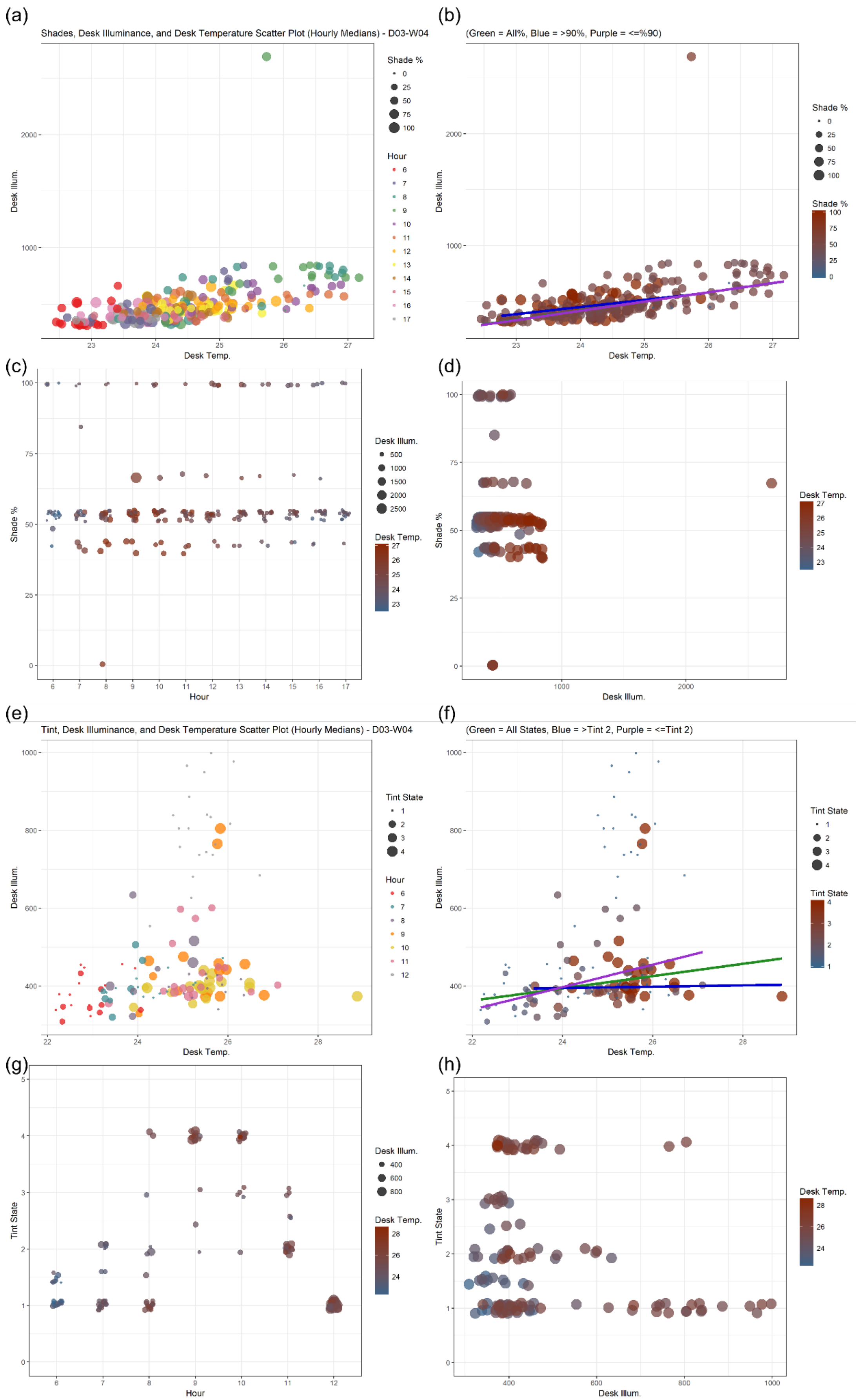

Figure S16. Assessments of the impact of (a-d) shade height and (e-h) tint level on desk-level illuminance and temperature at D03 during the Daylighting Study.

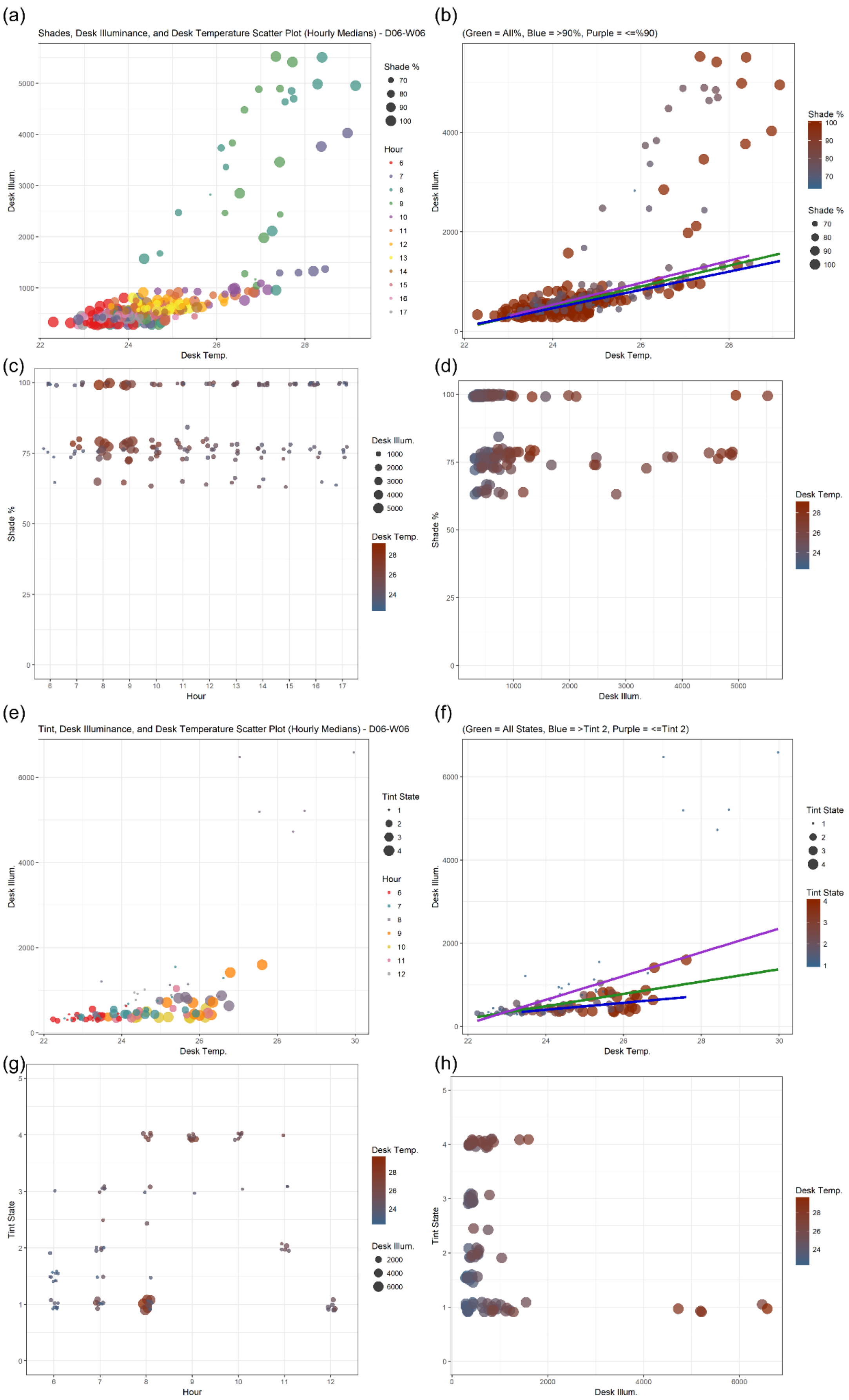

Figure S17. Assessments of the impact of (a-d) shade height and (e-h) tint level on desk-level illuminance and temperature at D06 during the Daylighting Study.

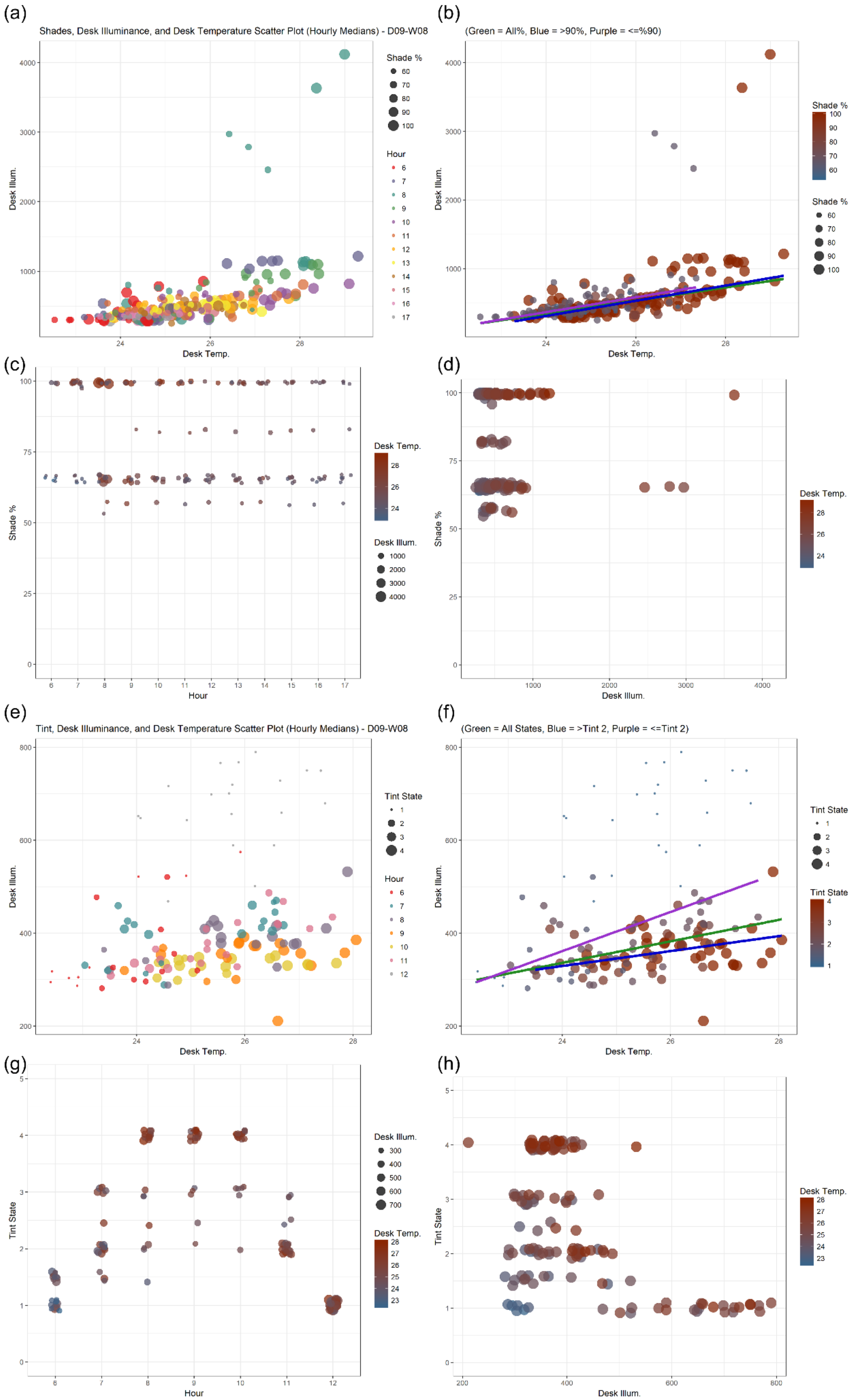

Figure 18. Assessments of the impact of (a-d) shade height and (e-h) tint level on desk-level illuminance and temperature at D09 during the Daylighting Study.

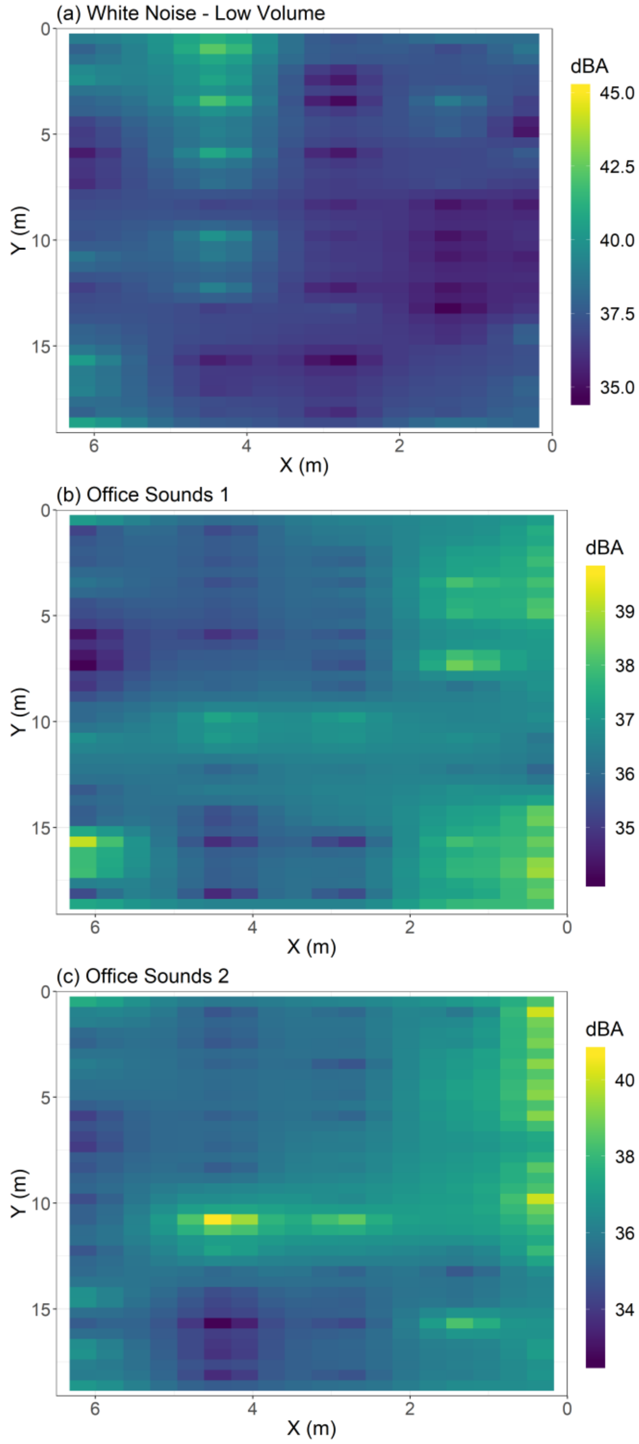

Figure S19. Spatial variability of sound levels (dBA) during the (a) low volume white noise, (b) office sounds 1, and (c) office sounds 2 conditions during the Multi-IEQ study.

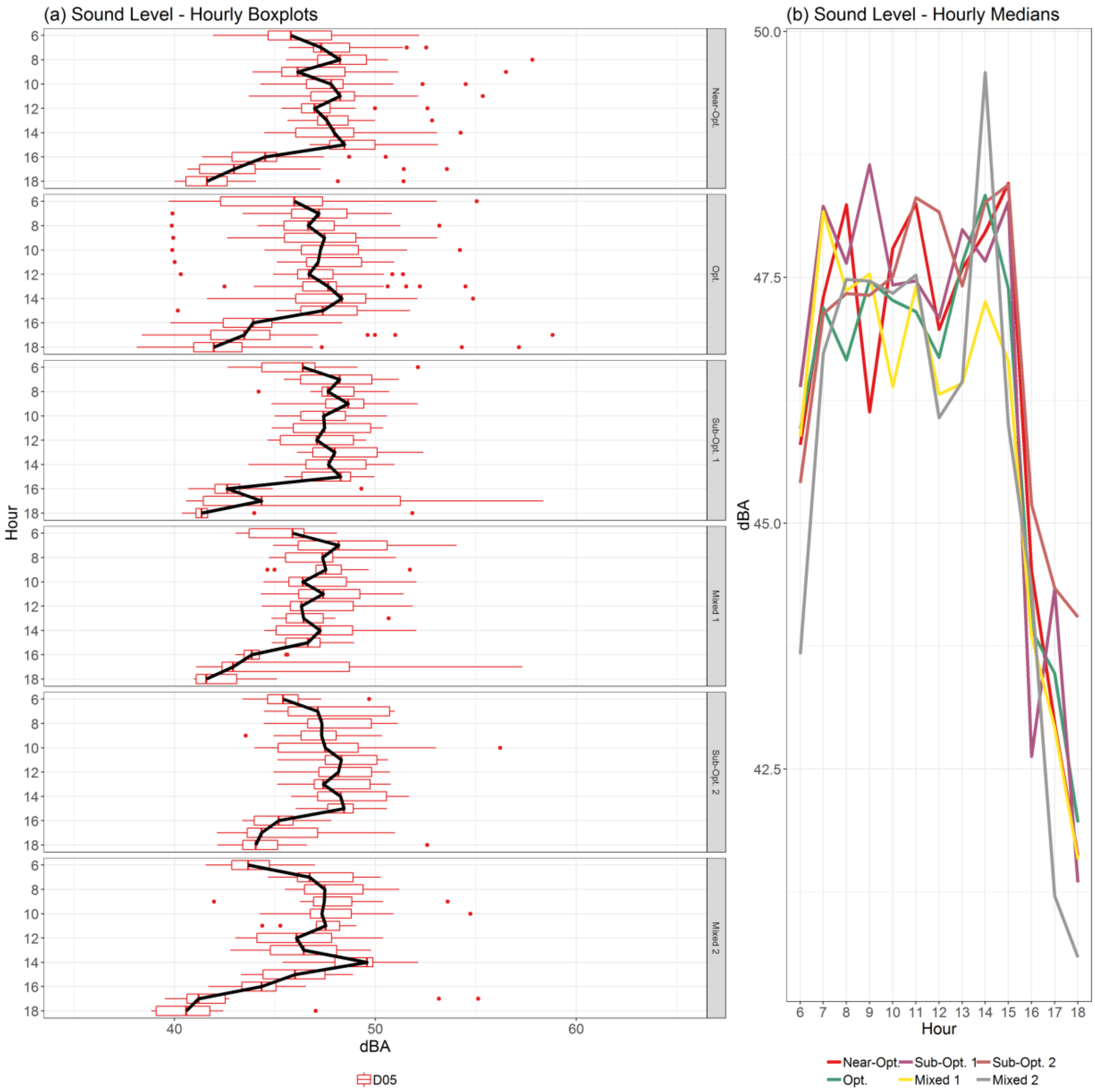

Figure S20. Temporal variability of office sound levels (dBA): (a) hourly boxplots per experimental condition and (b) hourly medians per experimental condition during the Multi-IEQ Study.

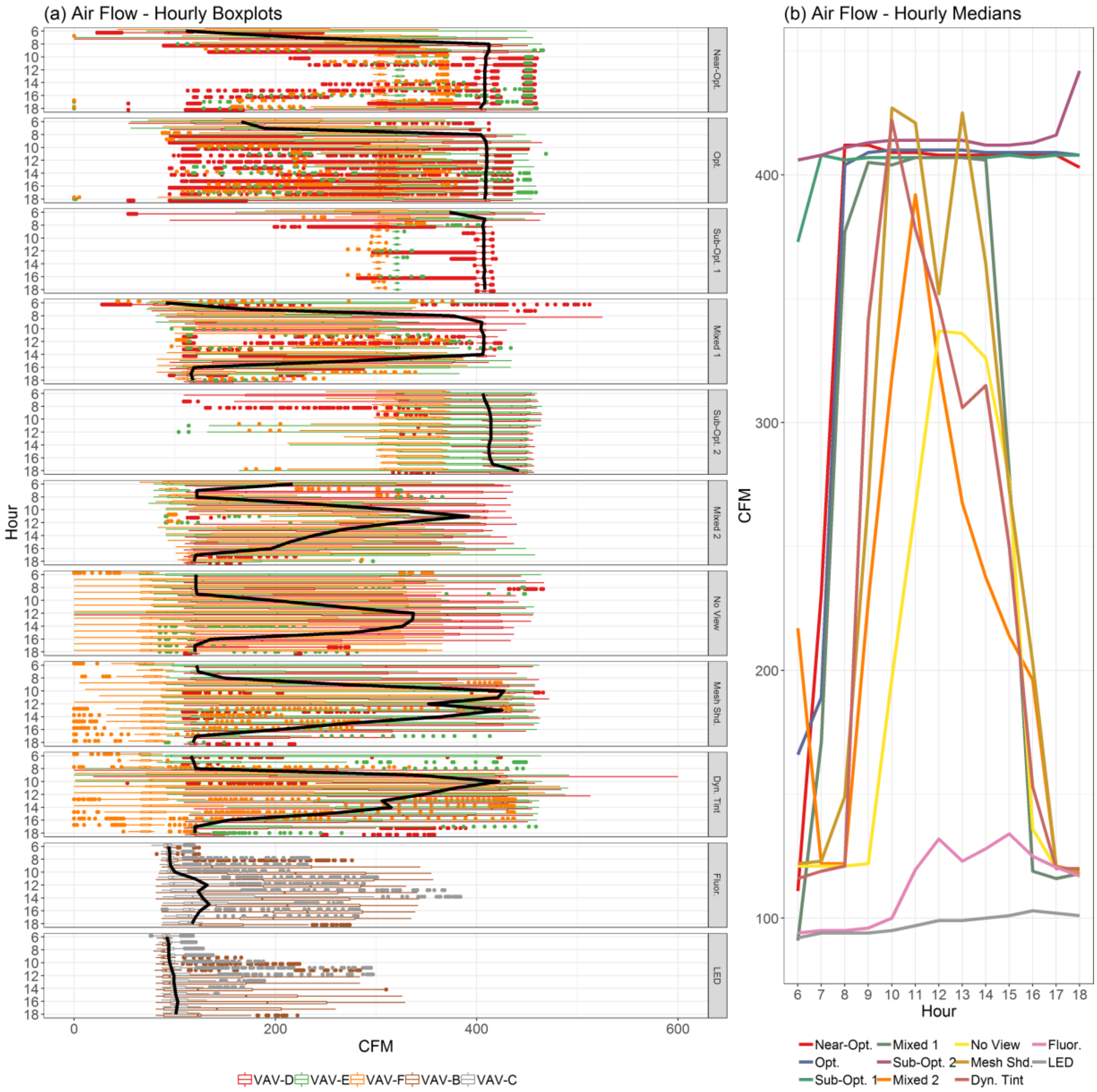

Figure S21. Temporal variability of VAV air flow (CFM): (a) hourly boxplots per experimental condition and (b) hourly medians per experimental condition during three office experiments.

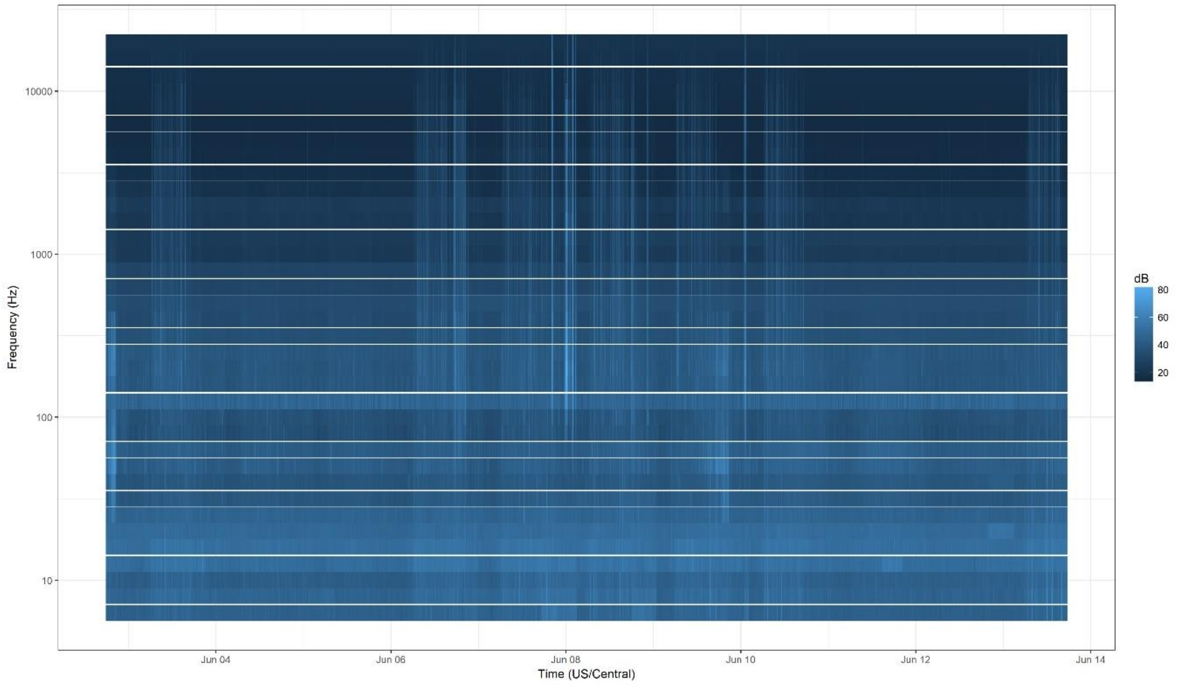

Figure S22. Temporal variability the audio spectrum during a representative week of the Multi-IEQ study.

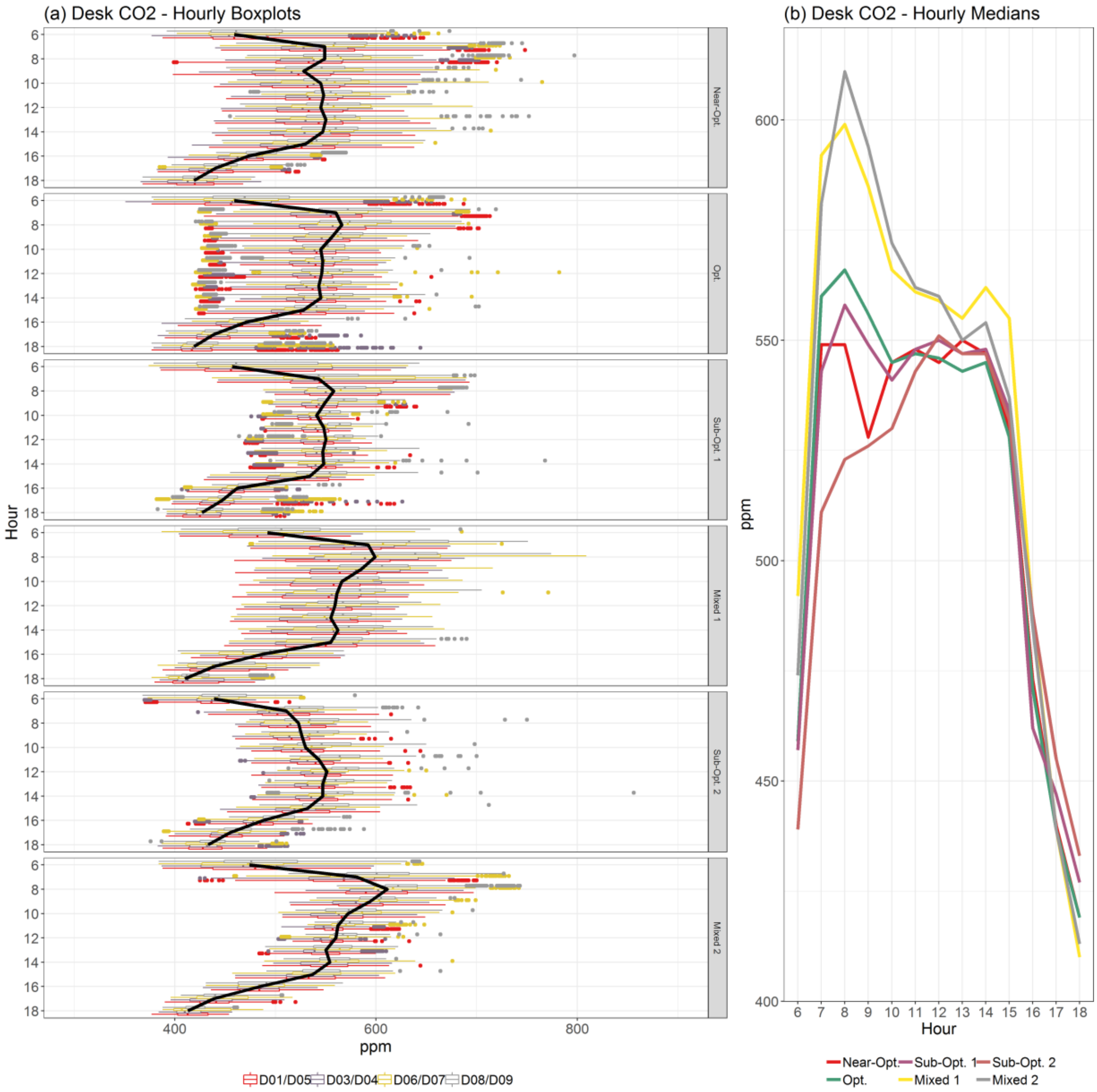

Figure S23. Temporal variability of CO_2 (ppm): (a) hourly boxplots per experimental condition and (b) hourly medians per experimental condition during the Multi-IEQ Study.