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Strategies to Achieve Optimum Visual Quality for Maximum Occupant Satisfaction: Field Study Findings in Office Buildings

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Abstract

For visual quality, the traditional focus on illuminance for paper-based tasks and brightness contrast for visual acuity is becoming less relevant in modern offices with backlit computer screens and sporadic use of paper. This research aims to investigate critical correlations between user satisfaction, workstation lighting conditions, and the physical attributes of the work area. The statistical analyses were conducted to identify applicable recommendations leading to improved visual quality in today's work environment while maintaining optimal user satisfaction.

Findings from post-occupancy evaluation on 1,232 workstations in 64 office buildings revealed that satisfaction level would increase by 20% on average when the occupants have seated view to the outside in their work area. Upgrading the ceiling light fixture with the indirect lens type could increase visual satisfaction. In particular, workstations with the indirect lens type had higher satisfaction (62%), while the prismatic ceiling lens type showed the lowest user satisfaction (34%). The analysis further identified that a combination of indirect light fixtures with task lights could increase user satisfaction by 21%. Lastly, utilizing window shading devices revealed greater satisfaction with glare management. The occupants who have external and internal shading devices in their work areas showed the highest satisfaction with their overall lighting. In addition to the recommendations mentioned above, the illuminance level identified to achieve maximum satisfaction is 406 lux for the work surface in contemporary office environments.

Keywords

Indoor environmental quality; Visual quality; Post-occupancy evaluation; Environmental satisfaction; Visual comfort

1 Introduction

Lighting plays an essential role in the quality of the indoor environment and contributes to the wellbeing, productivity, and satisfaction of occupants [1,2]. Field studies performed in the US office buildings showed that office workers' job satisfaction is highly correlated to the quality of lighting, such as illuminance levels and glares, in the space [3–5]. Aaras et al. [6,7] illustrated the strong correlation of lighting conditions to health-related visual discomfort through field studies. For instance, reducing glare from direct 'downlighting' from the ceiling by shifting to indirect lighting could lead to a 27% reduction in headaches [6]. Studies conducted from The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) on twelve international case studies showed improving lighting design could increase individual productivity between 0.7-23% while reducing annual energy loads by 27-88% [1,8].

The quality of the visual environment in the workplace is often measured by illuminance level (the amount of light falling on a particular point), luminance level (the amount of light emitted or reflected by a surface in a given direction) and glare [9]. In a typical office, the Illuminating Engineering Society of North America (IESNA) standard requires a maintained illuminance level of 500 lux on the working activities such as writing, reading, and typing [10].

For lighting performance evaluation, illuminance is commonly used in field studies because it is cheaper and easier to measure than luminance. However, the human eye responds more often to luminance, not illuminance. In a 2009 laboratory study conducted in Canada, Newsham et al. [11] suggested that luminance-based lighting control systems are better at delivering the lighting conditions that people prefer, while also reducing energy use. These physical environmental conditions serve as useful indices for lighting performance evaluation. As shown in Table 1, other indices, including spectrum, discomfort glare, flicker, and personal control, are often considered for lighting quality assessments and constitute useful indicators in visual comfort. In general, indicators are measurable against designated goals. Good indicators can afford to identify poor lighting conditions and uncover visual performance issues with associated health problems. For instance, an indicator of daylight control can be used to measure individual access to daylight that stimulates the production of the melatonin hormone for regulating the body's internal clock [12]. Lack of daylight contributes to sleep disturbance, fatigue, mood shifts, and depression, and adversely affects individual productivity and user satisfaction. In addition to air-related Sick Building Syndrome (SBS) symptoms, such as throat dryness and wheezing, light intensity was found to be significantly correlated with skin dryness, eye pain, and malaise [13,14]. Occupant satisfaction of indoor lighting quality can, therefore, be improved by increasing access to daylight, which in turn reduces the development of SBS symptoms and energy use.

Table 1 Indicators of visual quality assessment

Index	*Goal*	*IEQ related indicator*	*Sources*
Illuminance (lux, lm/m^2)	Amount of light falling on a task area	Light level	[15]
Luminance (cd/m^2)	Disability glare and reflections Uniformity and contrast	Human eye responds to luminance	[3,11]
Spectrum	Correlated color temperature (K) Color rendering (index)	Color rendering: the effect of a light source on the perceived color of objects and surfaces	[16,17]
Discomfort	Daylight glare probability	Uniformity and contrast	[10]

Index	*Goal*	*IEQ related indicator*	*Sources*
glare (cd/m^2)	Contrast Rendering Factor	Eyesore, eye blink frequency	[18]
Flicker	Noticeable rapid fluctuations in light level	Eyesore, eye blink frequency	[18–20]
Personal Control	Support individual productivity, health and user satisfaction	Light Control	[6,21–34]
		Daylight Control	[25,27,28,30,33,35–39]

When designing modern offices, applying prevailing standards and guidelines without considering the predominant computer-based tasks could lead to unsatisfactory lighting design and excessive energy use. A few studies suggested a need to adjust the recommended illuminance level of 500 lux by IESNA to accommodate dynamic lighting requirements for computer-based and paper-based activities [40,41]. The common findings suggested the separation of the ambient and task lighting to improve visual quality while reducing energy use. Albeit the measured illuminance level serves as a useful index for evaluating visual quality, very little attention was paid to distill critical factors from all collectible data, including technical building attributes, existing environmental conditions, and occupant satisfaction levels. These critical factors are envisaged to play a significant role in shaping applicable design strategies to ensure visual quality in modern indoor environments.

Our hypothesis is that humans are capable sensors for post-occupancy evaluation (POE). Combining occupant responses with essential indoor environmental quality (IEQ) indices can provide insight to inform design decisions and enhance occupant satisfaction. We expect to achieve optimal visual comfort by identifying correlations between measure IEQ, building systems, and user satisfaction in concurrent time frames. In this study, we conducted POE field studies in 64 office buildings to collect existing lighting quality indices with occupant satisfaction levels and technical building attributes. We examined the field measurement data to investigate applicable lighting design guidelines for office buildings and critical lighting thresholds to achieve the optimal visual quality for maximum occupant satisfaction.

2 Methods

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) developed the National Environmental Assessment Toolkit (NEAT) cart supported by the sponsor General Service Administration [42]. The NEAT cart aimed to support the simultaneous assessment of the thermal, visual, acoustic, air conditions at occupant workstations. Specifically, for the indoor environment's visual quality, hand-held instruments measure light levels on the monitor, work surface, and keyboard with a data logger connected to a tablet PC to record data. A single-lens reflex (SLR) camera with a fisheye lens is also equipped to capture the scene luminance for brightness contrast and glare analyses. NEAT has been deployed over 15 years in both public and private sector buildings to collect objective and subjective IEQ data at individual workstations [5]. A database was developed with accumulative POE field data from 64 office buildings from 2003 to 2014 [43].

In this paper, we mainly focused on the visual quality findings from IEQ field studies. We cross-examined the applications of three different data sources, including measured visual quality, Technical Attributes of Building Systems (TABS), and occupant satisfaction survey. A total of 1,254 workstations were selected for visual quality assessment from 64 buildings, including 33 federal and 31 private sector offices for financial, sales, and marketing. This study chose small- and medium-sized offices with less than 500 m^2 to facilitate cross-sectional analyses against codes for lighting quality assessment by IESNA [10]. The sampling rate of spot measurements was typically 30% of the total office workstations per floor, or minimum 15 workstations for a small workgroup, to cover a mix of open and closed, perimeter and core workstations. Sampling was conducted based on workstation locations (perimeter or core), orientations (north, south, east, or west), and office types (open or closed). Additional sampling was also taken to consider the idiosyncratic nature of the lighting system and variations in work tasks.

2.1 Measurements of Visual Quality in the Field

Illuminance levels on the work surface, computer monitors, and keyboards are measured when the task light is on and off using Konica Minolta T-10A light meter. Figure 1 illustrates the onsite IEQ measurements and the luminance and glare levels collected using Nikon Coolpix 5400 camera with a fisheye lens. For the luminance analysis, Konica Minolta Luminance Meter LS-100 was utilized for spot measurements and Photolux 2.1—a photometric diagnosis system—for luminance and visual comfort analysis [44].

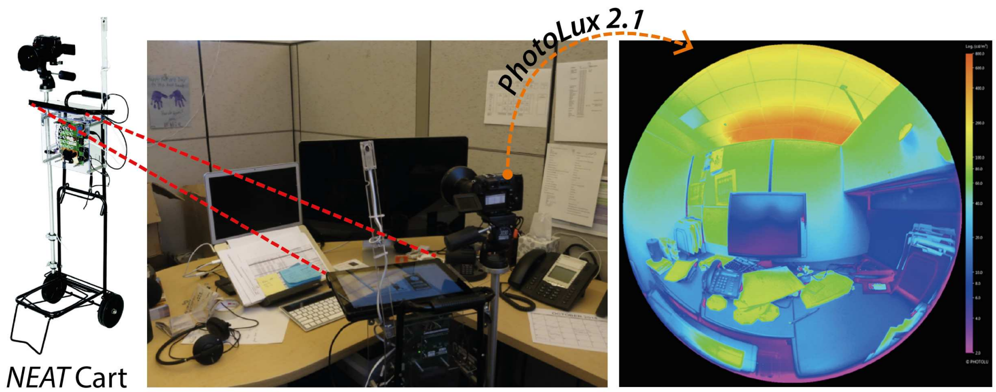


Figure 1 IEQ spot measurements in the field using NEAT cart and the luminance map generated by PhotoLux

2.2 Technical Attributes of Building Systems (TABS)

The aim of recording TABS is to identify the key physical attributes of the building and workplace that might significantly impact measured environmental conditions, and individual/organizational performance. Specifically, CBPD developed expert walkthrough records to ensure comparable data was recorded for the attributes of building systems that affect lighting and visual quality. Appendix A shows questionnaires of the technical attributes of building systems for visual quality evaluation and Appendix B for workstation contextual data.

2.3 Occupant Satisfaction Survey

The Cost-effective Open-Plan Environment (COPE) questionnaire developed by the National Research Council Canada was utilized in this study [39,45]. A few more questions were added for this research as a result of recommendations from the GSA field study, including Q11. Glare on the computer screen, Q12. Glare from electric lighting fixtures, and Q13. Glare from daylight [41,46,47]. The user satisfaction survey intends to understand how occupants experience their present work environments qualitatively. Each participant was asked to complete a "user satisfaction questionnaire" related to today's specific environmental conditions, as compared to annual satisfaction questionnaires when conducting workstation's IEQ measurements. The objective was to investigate the impacts of building physical and environmental conditions on occupancy satisfaction through statistical analysis.

This survey was distributed via paper or iPad to employees who occupied the workstations based on the sampling strategies mentioned above. Occupants were provided with essential project information and asked to give their content before undertaking the spot measurements and the user satisfaction survey.

2.4 Data Analysis

Among 1,232 workstations from 64 buildings, there were 531 female and 519 male participants between 18 and 69.

Table 2 shows the demographic information of the participants included in this study. As the demographic question was not mandatory, the received responses (n=1050) were less than the total IEQ measurements.

Table 2 Participant demographic information

Age	Female	Male	Total
20-29	116	132	248 (24%)
30-39	158	136	294 (28%)
40-49	124	120	244 (23%)
50-59	107	98	205 (19%)
60+	15	26	41 (4%)
unidentified	11	7	19 (2%)
Total	**531 (51%)**	**519 (49%)**	**1050**

Table 3 presents 33 variables that were initially collected in the field studies for IEQ measurements (n= 7), TABS (n=17), and COPE (n=9). “Seated view” in TABS refers to the workstation that provides a view to outside when being occupied by the user, regardless of the distance to the view. For instance, a workstation in a perimeter office may be categorized as “No view” due to high partitions. Preliminary statistical analyses were performed using SAS (v.9.3) [48]. After data screening with the correlation matrix, 16 variables, including five IEQ measurements, seven TABS, and four COPE questions, were chosen for further correlation analyses.

Table 3 Variables for visual quality data analysis

NEAT IEQ measurements	**TABS** Technical Attributes of Building Systems	**COPE** User satisfaction survey
• Illuminance on monitor with task light on/off * • Illuminance on keyboard with task light on/off * • Illuminance on work surface with task light on/off * • Luminance • Unified Glare Ratio* • Luminance Ratio* • Glare Ratio	• Ceiling light fixture type* • Ceiling light fixture shape* • Ceiling light lens type* • Ceiling light ballast type* • Ceiling light control* • Seated view to outside* • Shades • Task light* • Window configuration • Window shading controls • Window glazing • Shading coefficient • Visible transmission • Furniture panel color • Alignment of light fixtures • Computer screens • Availability of Light control	• Light on desk for paper-based tasks* • Light for computer work* • Aesthetic appearance of your office • Level of visual privacy within your office • Glare on the computer screen • Direct glare from light fixtures • Direct glare from daylight • Your access to a view of outside* • Quality of lighting*

* Selected for correlation analysis

The data set of this study consisted of 1,254 workstations sampled from 64 office buildings. In total, 1,232 COPE satisfaction questionnaires were collected from workstation occupants. Due to the nature of survey data, the number of responses received slightly varied from question to question in the COPE survey. The preliminary descriptive statistics showed that the work surface's mean illuminance level was 581 lux when the task light was on, or 471 lux when the task light was off (Table 4). Measured illuminance levels were grouped by four satisfaction survey questions, including (A) Quality of Lighting, (B) Access to view outside, (C) Light for paper-based tasks, and (D) Light for computer tasks. A more careful review of light levels relative to satisfaction across seven scales showed somewhat positive correlations. However, the difference was not statistically significant with the p-values mostly larger than 0.05 for satisfaction groups regardless of the task light status. The exceptions were group B's monitor and worksurface illuminance levels when the task light was off.

Table 4 Illuminance levels by IEQ measurements and COPE satisfaction survey

	Monitor / Off (lux)	Keyboard / Off (lux)	Worksurface / Off (lux)	Monitor / On (lux)	Keyboard / On (lux)	Worksurface / On (lux)	
MAX	3320	2400	4897	2128	1820	1980	
Mean	289	423	471	289	487	581	
Std Dev	247	282	352	206	283	291	
Std Err	7.05	8.05	9.95	7.96	10.93	11.14	
Count	1228	1229	1254	672	673	682	
Satisfaction Scale*	A. Mean Illuminance vs. Quality of lighting (n =1038)						Count (%)
1	282	356	450	354	530	509	38 (4%)
2	251	385	383	199	392	464	69 (7%)
3	272	403	460	303	459	621	108 (10%)
4	270	417	468	254	464	583	184 (18%)
5	271	420	454	278	483	569	186 (18%)
6	338	424	478	306	535	632	319 (31%)
7	292	442	486	337	545	660	134 (13%)
Average	293	417	464	290	497	599	
p-Value	0.09	0.77	0.76	0.07	0.20	0.06	
Satisfaction Scale	B. Mean Illuminance vs. Access to view outside (n =1039)						Count (%)
1	237	373	418	249	463	535	189 (18%)
2	253	420	433	261	521	604	134 (13%)
3	267	417	425	289	490	567	92 (9%)
4	308	424	482	287	520	603	118 (11%)
5	291	400	429	272	496	619	90 (9%)
6	322	400	457	324	484	638	201 (19%)
7	346	474	552	336	490	622	215 (21%)
Average	294	417	464	293	492	600	
p-Value	0.01**	0.10	0.04**	0.17	0.93	0.43	
Satisfaction Scale	C. Mean Illuminance vs. Light for paper-based tasks (n =1049)						Count (%)
1	246	292	289	291	404	422	26 (2%)
2	299	454	435	241	489	533	68 (6%)
3	264	406	416	281	455	563	83 (8%)
4	302	444	485	284	476	557	156 (15%)
5	281	395	474	260	472	608	171 (16%)
6	298	426	477	289	500	606	347 (33%)
7	320	429	491	356	565	677	198 (19%)
Average	296	421	468	292	497	600	
p-Value	0.75	0.29	0.25	0.21	0.40	0.07	
Satisfaction Scale	D. Mean Illuminance vs. Light for computer tasks (n =1036)						Count (%)
1	266	369	361	236	321	407	22 (2%)
2	281	390	403	257	460	512	71 (7%)
3	313	404	439	323	473	573	78 (8%)
4	277	419	462	260	445	579	192 (19%)
5	287	433	459	295	492	614	167 (16%)
6	299	419	480	288	522	611	347 (33%)
7	301	416	493	317	549	651	159 (15%)
Average	292	417	464	288	495	598	
p-Value	0.96	0.95	0.60	0.62	0.14	0.12	

** 1: Very Dissatisfied, 2: Dissatisfied, 3: Somewhat Dissatisfied, 4: Neutral, 5: Somewhat 6: Satisfied, 7: Very Satisfied*
*** p < 0.05, indicating statistical significance observed*

COPE satisfaction findings from 1,232 occupants in 64 office buildings revealed that 62% satisfied with the overall quality of lighting in the work area, 18% neutral, and 21% dissatisfied, as shown in Figure 2a. While higher than thermal satisfaction (55%) [50], the visual environment's satisfactory quality for modern-day tasks could still be improved. One noticeable area that could be investigated is the seated access to daylight and views. The result showed that only 49% were satisfied with the overall quality of lighting, and 18% were very dissatisfied (Figure 2b). Further review of satisfaction with lighting for paper-based and computer tasks revealed similar results to overall lighting satisfaction, with 68% and 65% satisfied (Figure 2c and Figure 2d).

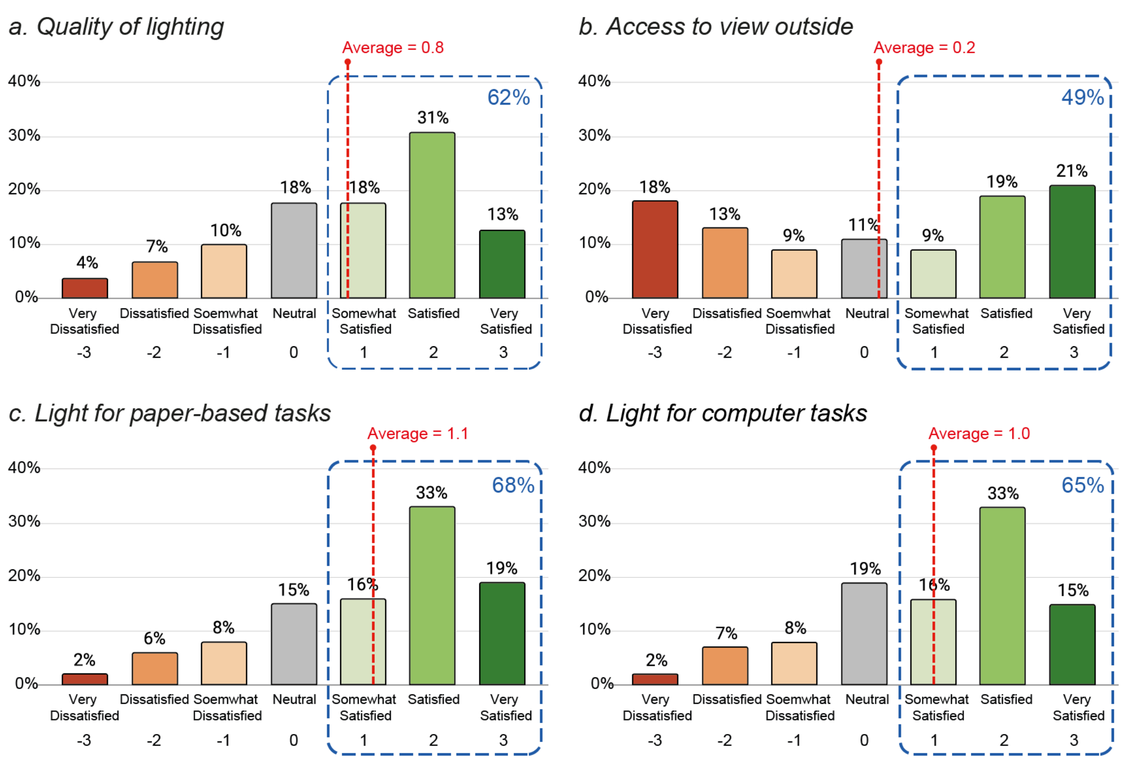


Figure 2 User satisfaction results in the work area. (a) Quality of lighting from 1,038 workstations; (b) Access to view outside from 1,039 workstations; (c) Light for paper-based tasks from 1,049 workstations; (d) Light for computer tasks from 1,036 workstations

Only looking at the descriptive statistics of the data set was insufficient to understand the extent to which environmental conditions impacted occupant satisfaction on the quality of lighting. A range of statistical methods was proposed to test the research hypotheses by correlating objective measurements on lighting conditions and building systems with subjective user satisfaction. The statistically significant findings would, in turn, inform actionable recommendations for code refinement and provide strategies to achieve optimal visual quality in high-performance work environments.

2.4.1 Correlation between workstation visual quality measurements (NEAT) and satisfaction on overall visual quality

The correlation between workstation visual quality measurements and user satisfaction was tested. Variables including gender, perimeter vs. core workstation location, and open-plan workstation vs. closed offices were also tested for correlation with workstation visual quality measurements. Three user satisfaction responses in the COPE questionnaires (light levels on the desk for paper-based tasks, light levels for computer work, and overall quality of lighting in your work area) and five visual quality measurements assessed by NEAT instrumentation were analyzed using ordinary least squares and ordered logistic fit. Satisfaction for overall lighting quality is found significantly correlated with the luminance ratio ($p<0.05$), as shown in Table 5.

Table 5 Correlation between workstation visual quality measurements and satisfaction on overall visual quality

Data Group	Code	Variables	Coefficient
NEAT	C-1	**Gender**	0.01
	C-2	**Perimeter-Core**	-0.38**
	C-3	**Open-Closed**	0.22
	NV-1	**Light level on monitor (lux)**	0.07

Data Group	Code	Variables	Coefficient
	NV-2	**Light level on keyboard (lux)**	0.11
	NV-3	**Light level on work surface (lux)**	0.04
	NV-4	**Luminance Ratio**	-0.28*
	NV-5	**Unified Glare Ratio**	-0.06

*p<0.05, **p<0.01, ***p<0.001

2.4.2 Correlation between technical attributes of building systems and satisfaction with overall visual quality

The correlation between technical attributes of building systems and user satisfaction with the overall visual quality was tested. Test variables include seven physical building attributes with respective sub-groups by lighting system types. As shown in Table 6, visual satisfaction is found significantly correlated with six physical attributes: (1) ceiling fixture type ($p<0.001$), (2) ceiling lens type ($p<0.01$), (3) ceiling light lamps ($p < 0.05$), (4) ceiling lens ballast type ($p<0.001$), (5) individual light control ($p<0.05$), and (6) seated view ($p<0.001$).

Table 6 Correlation between technical attributes of building systems and satisfaction with the overall visual quality

Visual Quality	Code	Variables	Coefficient
TABS –COPE	C-1	**Gender**	0.04
	C-2	**Perimeter-Core**	-0.48***
	C-3	**Open-Closed**	0.13
	TV-1-1	**Ceiling Fixture Type**	
	TV-1-2	2 by 2 vs. 2 by 4 or I / I-D w/hot spot	-0.08
	TV-1-3	2 by 2 vs. 1 by 4	0.36
	TV-1-4	2 by 2 vs. I-D without hotspots	0.88*
	TV-1-5	2 by 2 vs. I-D ambient & task	1.44***
	TV-2-1	**Ceiling Lens Type**	
	TV-2-2	Prismatic vs. Large cell parabolic	1.15*
	TV-2-3	Prismatic vs. Small/ medium cell parabolic	1.05*
	TV-2-4	Prismatic vs. I-D in 2x2 or 2x4 inset	2.71**
	TV-3-1	**Ceiling Light Lamps**	
	TV-3-2	Incandescent vs. T-12	0.25

	TV-3-3	Incandescent vs. T-8	0.73*
	TV-3-4	Incandescent vs. T-5, CFL	0.72*
	TV-4-1	**Ceiling Lens Ballast Type**	
	TV-4-2	Magnetic vs. Electronic Instant start	0
	TV-4-3	Magnetic vs. Electronic rapid start	0.19
	TV-4-4	Magnetic vs. Dimming electronic	1.71***
	TV-5-1	**Ceiling Light Control**	
	TV-5-2	No control vs. > 10 workstations	0.40
	TV-5-3	No control vs. 2-10 workstations	0.19
	TV-5-4	No control vs. Individual	0.22*
	TV-6	**Seated view vs. no view**	-0.61***
	TV-7	**Task light vs. no task light**	-0.27

*p<0.05, **p<0.01, ***p<0.001

2.4.3 Correlation between and technical attributes of building systems and workstation visual quality measurements

The correlation between technical attributes of building systems and workstation visual quality measurements was tested. Variables, including gender, perimeter vs. core workstation location, and open-plan workstations vs. closed office, were also included for correlation with workstation visual quality measurements. In this test, the correlations between the five visual quality measurements assessed by NEAT instrumentation and seven physical building attributes investigated in the TABS records were analyzed using ordinary least squares and ordered logistic fit.

Among visual quality measurements, the illuminance level on the work surface showed the strongest correlation to the technical attributes of building systems. Ceiling fixture type ($p<0.05$), ceiling light lamp ($p<0.001$), dimming electronic ($p<0.05$), and seated view ($p<0.01$) showed significant correlations with measured illuminance levels on the work surface, as shown in Table 7.

Table 7 Correlation between and technical attributes of building systems and workstation visual quality measurements

Visual Quality	Code	Variables	Coefficient
TABS - NEAT	C-1	**Gender**	1.02
	C-2	**Perimeter-Core**	-2.48*
	C-3	**Open-Closed**	1.32
	TV-1-1	**Ceiling Fixture Type**	
	TV-1-2	2 by 4	1.13
	TV-1-3	1 by 4	1.24
	TV-1-4	I-D without hotspots	1.72
	TV-1-5	I-D ambient & task	2.17*
	TV-2-1	**Ceiling Lens Type**	
	TV-2-2	Flush/ K-16 prismatic lens	-1.07
	TV-2-3	Large cell parabolic	-1.67
	TV-3-1	Medium or small cell parabolic	0.28
	TV-3-2	I-D in 2x2 or 2x4 inset	-1.19
	TV-3-3	**Ceiling Light Lamps**	
	TV-3-1	T-12	-3.46***
	TV-3-2	T-8	-0.45
	TV-3-3	T-5, CFL	-2.78**
	TV-4-1	**Ceiling Lens Ballast Type**	
	TV-4-2	Electronic Instant start	1.09
	TV-4-3	Electronic rapid start	1.18
	TV-4-4	Dimming electronic	2.02*
	TV-5-1	**Ceiling Light Control**	
	TV-5-2	> 10 workstations	0.26
	TV-5-3	2-10 workstations	1.41
	TV-5-4	Individual	0.68
	TV-6	**Seated view vs. no view**	2.9**
	TV-7	**Task light vs. no task light**	0.62

*p<0.05, **p<0.01, ***p<0.001

2.4.4 Correlation of user satisfaction with a combination of technical attributes of building systems and workstation visual quality measurements

In Figure 3, the correlation between user satisfaction and all technical and environmental variables was tested. Additional contextual variables, including gender, perimeter versus core workstation location, and open-plan workstation versus closed offices, were also tested for correlation with user satisfaction. In this step, the correlation between a total of twelve variables (seven physical attributes investigated in TABS record and five sets of workstation visual quality measurements assessed by NEAT) and three user satisfaction responses investigated in the COPE questionnaires (lighting on the desk for paper-based tasks, light for computer work and overall quality of lighting in your work area) were analyzed using ordinary least squares and ordered logistic fit.

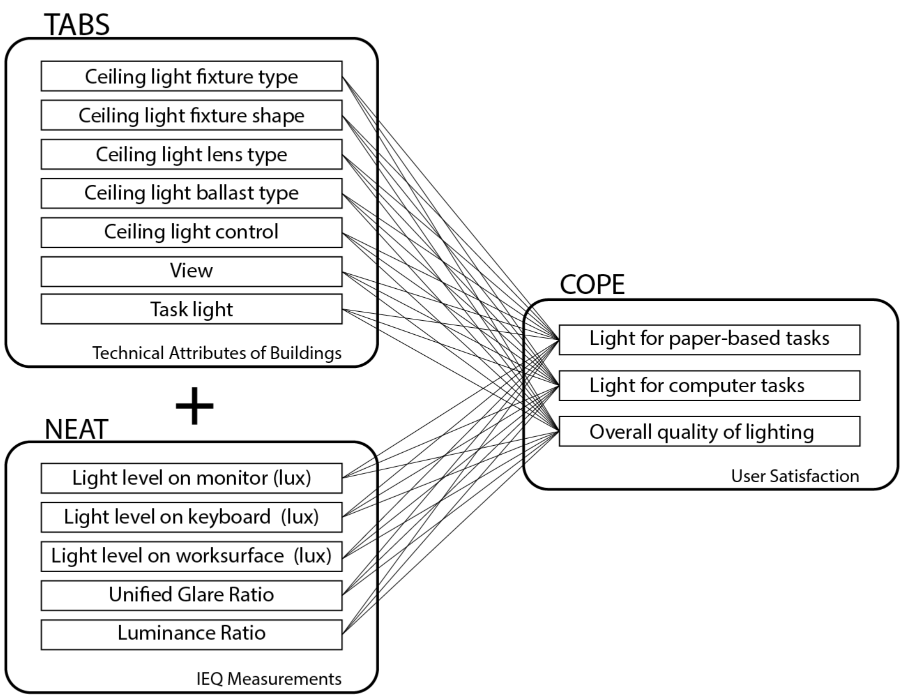


Figure 3 Combination of buildings systems and measured IEQ with user satisfaction in visual quality correlation analysis

Table 8 illustrates the combination of technical attributes of the building systems and workstation visual quality measurements that significantly correlate user satisfaction with the overall quality of lighting. Statistically significant factors include (1) ceiling fixture type ($p<0.05$), (2) ceiling lens type ($p<0.05$), (3) illuminance level on the computer monitor(p<0.05), (4) illuminance level on the keyboard (p<0.05), and (5) illuminance level on work surface (p<0.05).

Table 8 Correlation of user satisfaction with a combination of technical attributes of building systems and workstation visual quality measurements

Visual Quality	Code	Variables	Coefficient
TABS + NEAT	C-1	**Gender**	0.31
	C-2	**Perimeter-Core**	-0.69*
	C-3	**Open-Closed**	0.31
	TV-1-1	**Ceiling Fixture Type**	
	TV-1-2	2 by 2 vs. 2 by 4 or I / I-D w/hot spot	0.48
	TV-1-3	2 by 2 vs. 1 by 4	0.62
	TV-1-4	2 by 2 vs. I-D without hotspots	0.56
	TV-1-5	2 by 2 vs. I-D ambient & task	1.62*
	TV-2-1	**Ceiling Lens Type**	
	TV-2-3	Prismatic vs. Large cell parabolic	-0.17
	TV-3-1	Prismatic vs. Small/ medium cell parabolic	0.03*
	TV-3-2	Prismatic vs. I-D in 2x2 or 2x4 inset	0.18
	TV-3-3	**Ceiling Light Lamps**	
	TV-3-1	Incandescent vs. T-12	0.1
	TV-3-2	Incandescent vs. T-8	0.35
	TV-3-3	Incandescent vs. T-5, CFL	0.17
	TV-4-1	**Ceiling Lens Ballast Type**	
	TV-4-2	Magnetic vs. Electronic Instant start	0.39
	TV-4-3	Magnetic vs. Electronic rapid start	0.08
	TV-4-4	Magnetic vs. Dimming electronic	0.66
	TV-5-1	**Ceiling Light Control**	
	TV-5-2	No control vs. > 10 workstations	-0.13
	TV-5-3	No control vs. 2-10 workstations	0.36
	TV-5-4	No control vs. Individual	0.49
	TV-6	**View**	-0.52
	TV-7	**Task Light**	0.20
	NV-1	**Light level on monitor**	0.26*
	NV-2	**Light level on keyboard**	0.28*
	NV-3	**Light level on work surface**	0.20*
	NV-4	**Luminance Ratio**	-0.65
	NV-5	**Unified Glare Ratio**	-0.18

*p<0.05, **p<0.01, ***p<0.001

2.4.5 Correlation of user satisfaction with the interaction of technical attributes of building systems and workstation visual quality measurements

In this test, the correlation analysis was performed to identify the extent to which the interaction of technical attributes of building systems and workstation's IEQ measurements would affect user satisfaction. All variables (seven technical attributes of building systems and five IEQ measurements) were tested against user satisfaction using ordinary least squares and ordered logistic fit, as shown in Figure 4.

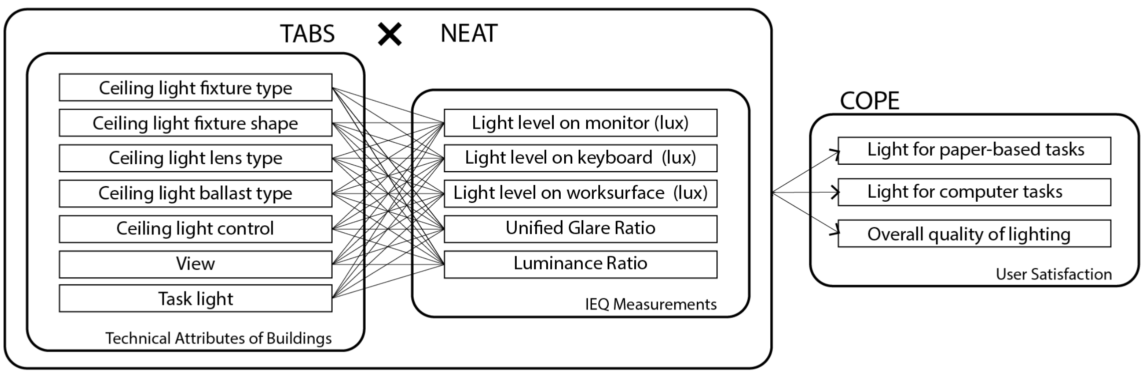


Figure 4 Interaction with technical attributes of building systems and IEQ measurements with user satiation in visual quality

In this study, we conducted a Wald test to define the workstation's IEQ thresholds of visual satisfaction. Table 9 shows the summary of visual quality thresholds by perimeter versus core workstation location for the workstation's illuminance on the monitor, keyboard, and work surface that led to the highest user satisfaction for overall lighting satisfaction.

Table 9 Workstation's visual quality thresholds for highest user satisfaction by perimeter vs. office location

Variable	Core Office	Perimeter office
Illuminance on monitor (lux)	290.5	297.1
Illuminance on keyboard (lux)	406.2	413.4
Illuminance on work surface (lux)	406.4	404.1

3 Results and Visual Quality Analysis

3.1 Seated view & daylight for greater satisfaction and higher light levels

Satisfaction levels increase when the occupants have seated view to outside in their work areas. From the seated view distribution from 1,232 questionnaire respondents in 64 buildings, 59% of the workstations do not have a view to outside, and 41% have a seated view. The seated view has a significant correlation with three visual quality satisfaction questions, including (1) view to outside ($p<0.001$), (2) quality of lighting ($p<0.01$), and (3) light for paperwork ($p<0.05$). On average, occupants in seated view workstations showed 70% of user satisfaction and around 50% for no view workstations, as shown in Figure 5.

Figure 5 User satisfaction of view to outside, overall quality of lighting and light for paperwork by the seated view and no view workstations in 64 buildings

3.2 Indirect ceiling lights and task lights for greater satisfaction

Satisfaction levels increase when the occupants have indirect ceiling lights and individual task lights in their workstations. The TABS for ceiling light fixture was differentiated by the five categories - 2 by 2, 2 by 4, 1 by 4, indirect ambient light only, and indirect ambient light with task light.

Figure 6 illustrates five ceiling light fixtures and the distribution from 980 questionnaire respondents in 64 buildings divided by workstations with and without the seated view. 64% of the offices had two by four or one by four type ceiling light fixtures. About 22% of workstations had indirect ceiling lights, and 5% of offices had indirect light fixtures with task lights.

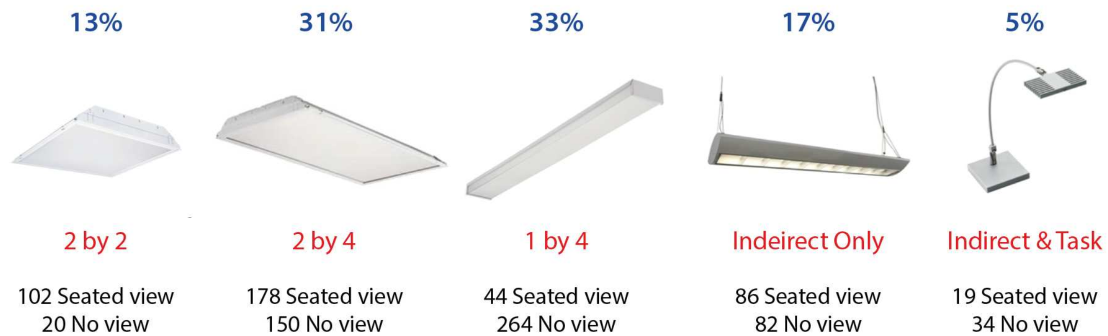


Figure 6 Distribution of ceiling light fixture for 980 questionnaire respondents in 64 buildings (divided seated view and no view workstation locations)

Satisfaction with lighting quality increased with the combination of indirect ceiling light fixtures and a task light for no seated view workstations ($p<0.05$). The occupants who had indirect ceiling lights with their own task lights were highly satisfied with their overall light quality, on average, 82% of users were satisfied. In comparison, about 58% of occupants were dissatisfied with two by two ceiling light fixtures, as shown in Figure 7. The ceiling light fixture effect was only critical in the workstations with no seated views ($p=0.004$) and had no strong relation in seated view workstations ($p=0.19$).

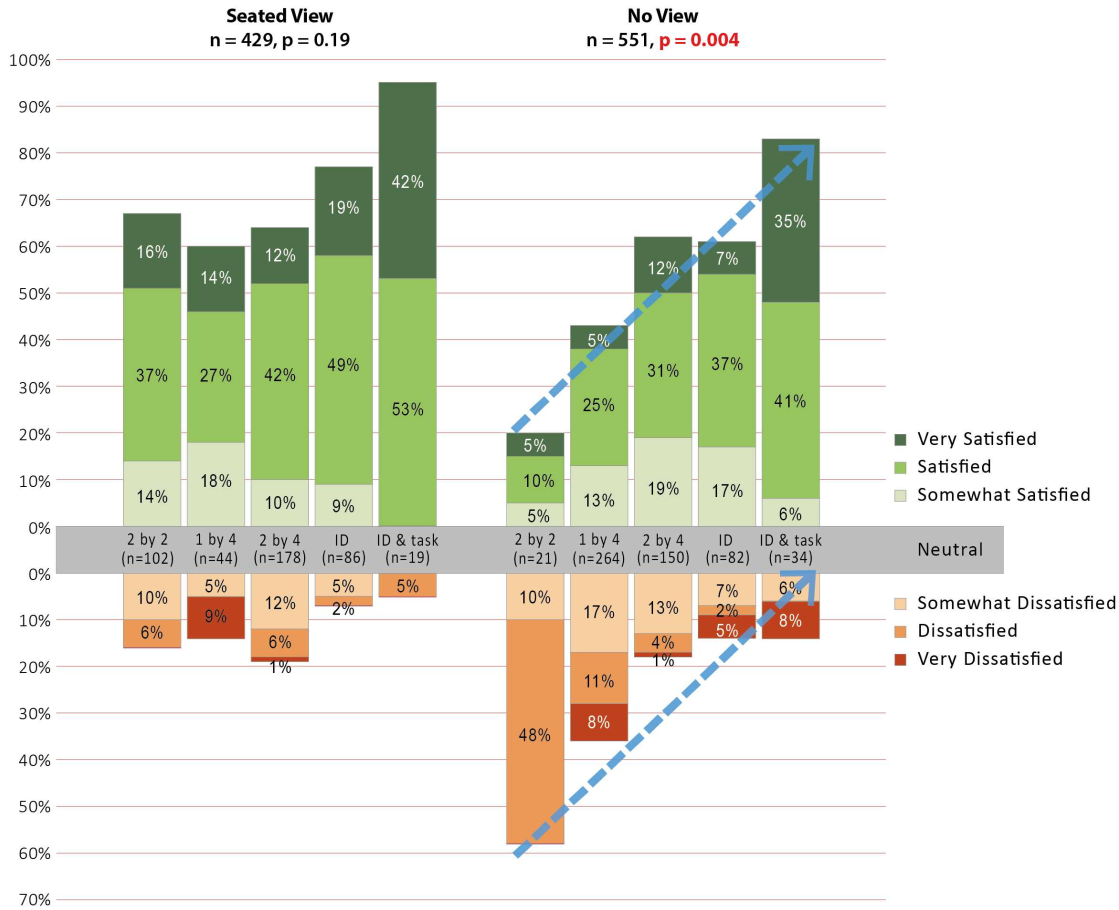


Figure 7 Visual Satisfaction by ceiling light fixture for the seated view and no view workstations (n=980)

3.3 Ceiling lens type for greater satisfaction, higher light levels, and glare management

The lens type of ceiling lights plays a measurable role in delivering light to the work surface and managing direct and indirect glare from light fixtures. Statistical analysis revealed that the lens type was significant for perimeter workstation areas (n=683). Upgrading ceiling lens type can increase user satisfaction with the quality of lighting in a work area, particularly, with no seated view to outside. The TABS record of the ceiling lens type has four categories—prismatic, large parabolic, small or medium parabolic, and indirect lens type. About 41% of workstations had large, 14 % workstations with medium parabolic, and 26% had an indirect ceiling lens from 683 open-plan workstations in 64 buildings.

User satisfaction for overall lighting increased with the indirect ceiling lens type in the workstations with no seated views, as shown in Figure 8. There was a statistical difference with the ceiling lens type. On average, indirect lens type had higher satisfaction (62%), while large parabolic (54%) and medium/small parabolic lens types (55%) showed lower visual satisfaction. Especially, the prismatic celling lens type showed the lowest user satisfaction (34%). The satisfaction showed an upward trend when the ‘covers’ on light fixtures were no longer flush prismatic lenses or large cell parabolic louvers, both of which could contribute to direct and indirect glare from light sources. The effect of the ceiling lens type was only critical in the no seated view workstations ($p < 0.01$) and had no strong relation in the seated view workstations ($p=0.08$). This finding suggests the dominant influence of the ceiling fixture lens type on workstations with no view for occupant satisfaction.

Figure 8 Visual satisfaction by ceiling fixture lens type for the seated view and no view workstations in perimeter workstations (n=683)

3.4 Window shading devices for greater satisfaction and glare management

Shading type can affect user satisfaction. The visual TABS for shading type was differentiated by the five categories, including (1) no control, (2) roll down, (3) vertical, (4) horizontal, and (5) external and internal. The effect of the shading type was only critical in the workstations with seated views ($p < 0.05$) and had no strong relation in the no seated view workstations ($p > 0.05$). The left image of Figure 9 illustrates the distribution of the shading types from 997 questionnaire respondents in 64 buildings divided between 'seated views' and 'no seated view' workstations. 45% of the offices were controlled by horizontal blinds (n=452), 37% by vertical blinds (n=370). About 3% of workstations (n=30) had both external and internal shading devices in their work area.

Overall, the occupants with a seated view showed high satisfaction (above 50%) on overall visual quality in their work area. When they had more control, such as external and internal shading devices, about 90% of responses were satisfied with their work area's visual environment. For occupants without controllable shading devices, there was up to 30% dissatisfaction.

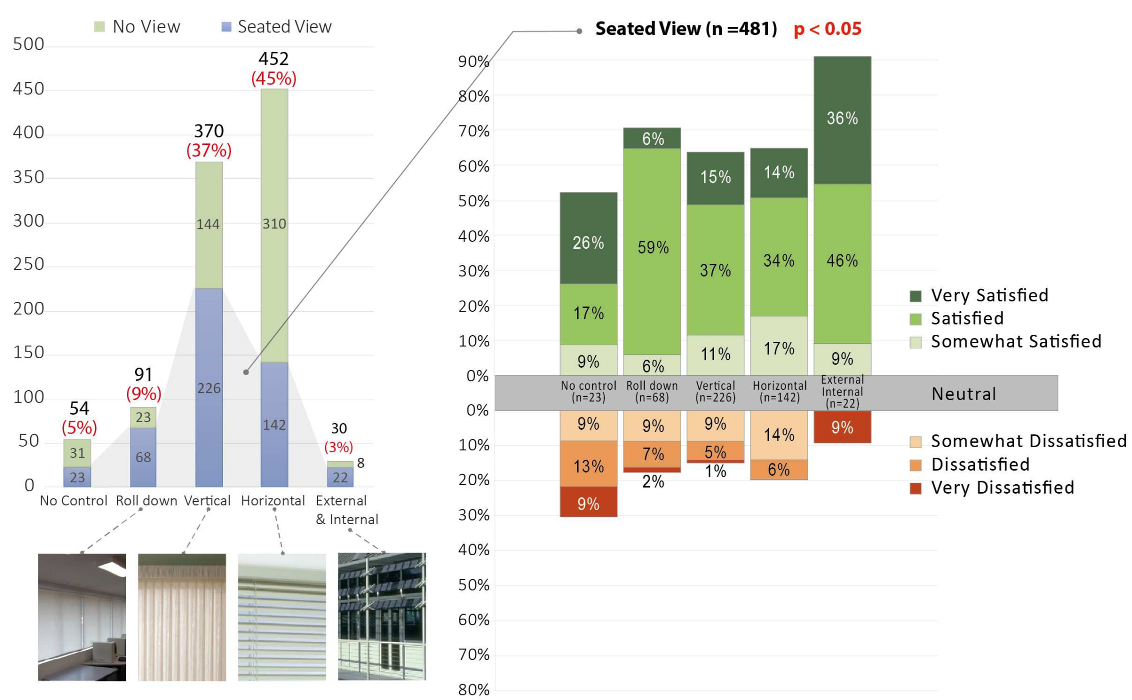


Figure 9 Visual satisfaction by shading type in seated view workstations (n=481), More shading controls = Greater Satisfaction

3.5 Managing illuminance on the work surface for greater satisfaction and code compliance

The illuminance levels from measured workstations in 64 buildings revealed that the average workstation light level (with the task light on) was 581 lux. 46% of workstations were below the Illuminating Engineering Society of North America (IESNA) recommended level of 500 lux for paper-based tasks, suggesting that more articulated arm task lights would be needed, as shown in Figure 10. When the task light was off, up to 65% of the workstations had the illuminance level under the IESNA recommendation, and the average illuminance level was around 471 lux.

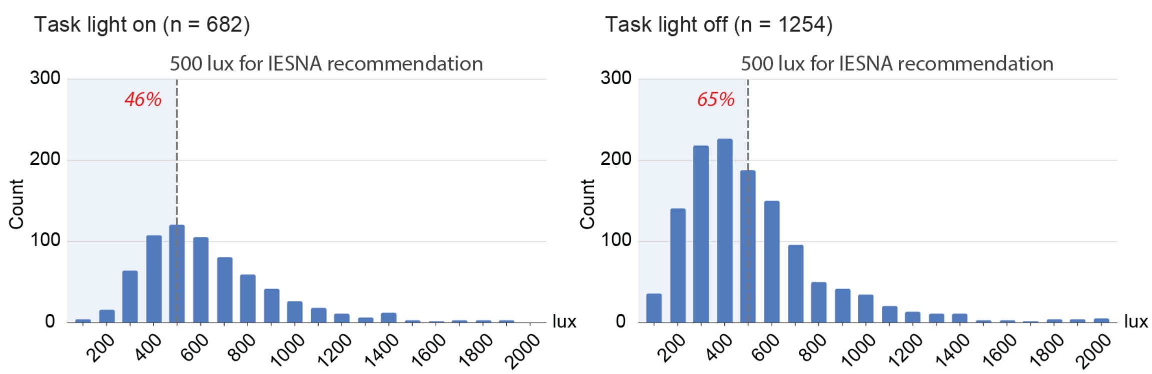
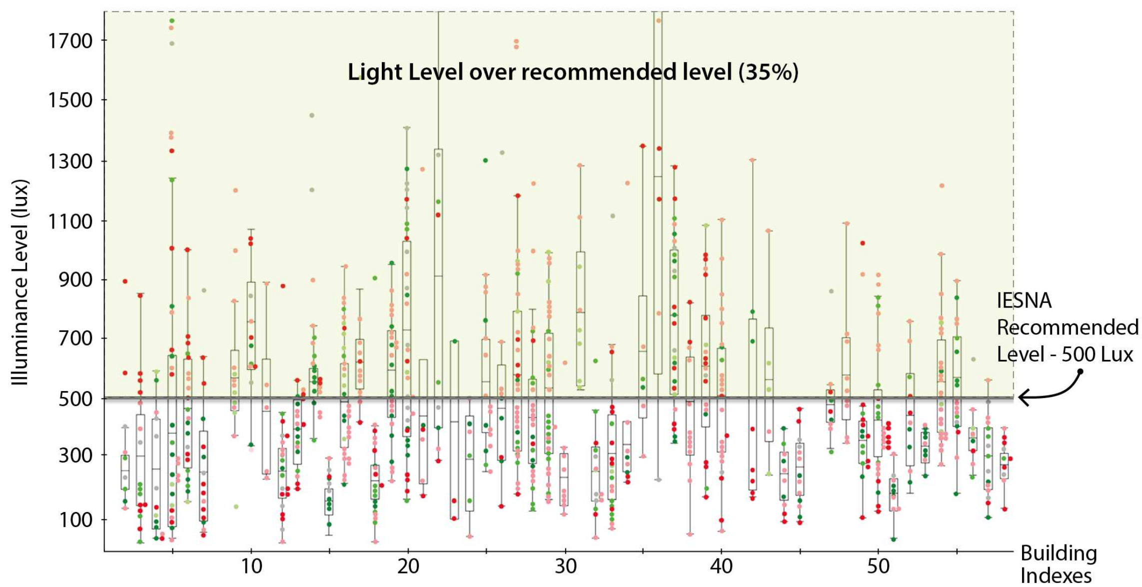


Figure 10 Workstations grouped by the task light status and IESNA 500 lux threshold

Figure 11 illustrates the measured light levels with the user satisfaction survey results from 1,254 work surfaces in 64 buildings. The observed variations among measured illuminance levels were substantial, ranging from less than 50 lux to more than 1,200 lux. The descriptive statistical analysis of the user satisfaction survey results concluded that there is no strong relation between measured illuminance level and user satisfaction.



1. 1206_GBA, 2. AMG10_THO, 3. AMG17_THO, 4. AMG24_THO, 5. AMG27_THO, 6. AOC_WDC, 7. BD1_PHL, 8. Bel_1BD, 9. Bel_2BD, 10. Bel_3BD, 11. BoA_BD1, 12. BoA_BD2, 13. BoA_BD3, 14. BOA_NYC, 15. CSL_PIT, 16. DFC_DEN, 17. DOJ_DEN, 18. DOL_SFO, 19. DVA_RNO, 20. EDF_B, 21. EDF_C, 22. EDF_D, 23. EDF_P, 24. EDF-H, 25. EDF-O, 26. EDO_ACC, 27. FAA_WDC, 28. FNQ_SAO, 29. FSS_CHI, 30. FSS_WDC, 31. FWT_FWT, 32. Geh_LA, 33. GPO_KNC, 34. HHS_SFO_1BLDG, 35. HHS_SFO_2BLDG, 36. MCS_PIT, 37. NPS_1, 38. NPS_2, 39. NPS_OMH, 40. OMP_Nor, 41. Paa1_PIT, 42. paa2_PIT, 43. PAC_PIT, 44. PBTC_PHL, 45. SCA_PIT, 46. SCR_RIO, 47. SEA_new_PIT, 48. SEA_old_PIT, 49. SER_SPO, 50. SFB_Atl, 51. SSA_JPL, 52. SSA_WDL, 53. TPL_PIT, 54. UBB_SPO, 55. UC2SPO, 56. UCG_ALM, 57. UCG_SFO, 58. UTC_HRF, 59. UTC_URF, 60. VIV_SPO, 61. WFC_N-17, 62. WFC_N-22, 63. WFC_S-40, 64. WFC_S-5.

Figure 11 Work surface light levels by building with colour-coded user satisfaction results

4 Discussion

Given the NEAT database from 64 buildings, 79% of occupants responded "satisfied" or "neutral", and 21% of occupants reported "dissatisfied" with their visual quality conditions. The average visual satisfaction level is 4.8, which falls between "neutral" and "somewhat satisfied" with their satisfaction on a 7-point scale (n=1,038, b=64, $p<0.001$). Five applicable design strategies to achieve higher user satisfaction in office environments are identified as follows:

Seated View: Among 1,232 workstations in 64 buildings in the NEAT database, 41% had a seated view, while 59% did not have a view to the outside. On average, occupants who have a seated view showed 20% higher satisfaction for visual quality.

Ceiling Light Fixture: Given the distribution of ceiling light fixtures for 980 questionnaire respondents in 64 buildings, 64% of the offices had 2x4 or 1x4 type ceiling light fixtures. About 22% of workstations had indirect ceiling light, and 5% of offices had indirect light fixtures with task lights. Visual satisfaction increased with better light fixtures in workstations without seated views ($n=980$, $p<0.05$). The occupants who had indirect ceiling lights with their own task lights were highly satisfied with their overall visual quality. On average, 82% of users were satisfied, while only about 20% of occupants were satisfied with 2x2 ceiling light fixtures. Using indirect light fixtures with task lights can increase user satisfaction by 21% compared to indirect light fixtures only.

Ceiling Lens Type: Upgrading the ceiling lens type could increase visual satisfaction. About 55% of workstations had a large or small/ medium parabolic lens, while 26% had the indirect ceiling lens. Visual satisfaction would be increased with an indirect ceiling lens type in the workstations with no seated views. On average, workstations with the indirect lens type had higher satisfaction (62%), while the prismatic celling lens type showed the lowest user satisfaction (34%).

Shading Type: Given the distribution of shading type surveys from 997 questionnaire respondents in 64 buildings, 82% of the offices were controlled by either horizontal blinds (45%, n=452) or vertical blinds (37%, n=370). About 3% of workstations had both external and internal shading devices in their work areas. Among 481 respondents who had seated views, occupants with both external and internal shading devices showed the highest satisfaction, and around 90% of occupants were satisfied with their overall lighting.

Light level on work: Given the measured illuminance levels from 1,254 workstations in 64 buildings, the average workstation light level (as-is conditions) was 581 lux. 54% of the workstations with the task light on exceeded the IESNA recommended level of 500 lux. When the task lights were off, the average illuminance level was 471 lux, and still, 35% of workstations were above the recommended threshold. Given the dataset, thresholds for maximum satisfaction level is found 406 lux on the work surface and 290 lux for monitors in office environments. Increasing the illuminance level above 406 lux will not significantly improve the visual quality of the workplace. The identified threshold for monitors is much lower compared to standard work surfaces. Different lighting level thresholds in the office environment suggest a more flexible and adaptable design strategy needed to accommodate needs in contemporary office environments while envisaging an increasing usage of monitors in occupants' daily tasks.

5 Conclusion and Limitation of the Study

In this study, we conducted post-occupancy evaluation (POE) to develop applicable design recommendations that contribute to optimal visual quality in the field while maintaining maximum occupant satisfaction. The presented integrated approach to POE combined IEQ measurements, technical attributes of building systems, and user satisfaction surveys to quantify the holistic conditions. Through field measurements, this study showed the concurrent lighting conditions of office environments. With the dataset of IEQ conditions from 1,232 workstations in 64 office buildings, user satisfaction is found closely linked with the seated view. A 20% increase on the satisfaction level could be reached when occupants have seated view to the outside in their workstations. Among these occupants, the added consideration of window shading devices, both internally and externally, could reach the highest 90% satisfaction level. For others who have no seated view to the outside, the satisfaction level is around 62% with the application of the indirect lens type or indirect light fixtures. In particular, around 80% of occupants are satisfied with the overall lighting quality by integrating indirect lighting and task lights. This finding supports the customizable individual lighting control will enhance user satisfaction.

Further analyses were carried out to examine impacts from the illuminance levels on user satisfaction. The findings suggest that illuminance levels for maximum user satisfaction are 406 lux for the work surface and 290 lux for monitors in contemporary office environments. This result deviates from the standard one-size-fits-all code compliance. To maximize user satisfaction, variable illuminance levels are recommended to support dynamic occupant needs. In this study, the limitations were the short-term spot measurements in one season per building and the less controllable nature of field measurements from an existing mixed quality building stock. Dependent on interpretations of experts in the field could also lead to the variation between observed and actual for the technical attribute records.

For future work, the advancement in both environmental sensing and communication technology is envisaged to improve further the efficiency of holistic IEQ monitoring at a fraction of cost. The long-term continuous IEQ conditions will become available to supplement existing onsite field measurements for in-depth diagnoses. Ultimately, conducting IEQ assessments at a sizeable spatiotemporal scale is anticipated to afford a robust prediction of user satisfaction on building performance. It will also contribute to developing metrics and guidelines for IEQ standards that capture critical thresholds for the highest building occupants' satisfaction.

Abbreviations

ANOVA: Analysis of variance

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

COPE: Cost-effective Open Plan Environments

EPA: US Environmental Protection Agency

IEQ: Indoor Environmental Quality

IESNA: Illuminating Engineering Society of North America

I-D: In-direct ambient light

NEAT: National Environmental Assessment Toolkit

OSL: Ordinary Least Squares

POE: Post-Occupancy Evaluation

PSE: Pseudo Standard Error

SBS: Sick Building Syndrome

TABS: Technical Attributes of Building Systems

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Appendices
A. Selected Technical Attributes of Building Systems: Visual Quality

Lighting: **for ____ floor, answer as many characteristics as possible for the most typical workstation**

Ceiling fixture type & shape:	☐ 2’ x 2’ ☐ 2’ x 4’ ☐ 1’ x 4’ ☐ I-D below ceiling/ pendular ☐ I-D in ceiling ☐ Other
Ceiling light lens type:	☐ Flush prismatic lens ☐ Small cell parabolic ☐ Medium cell parabolic ☐ Large cell parabolic ☐ Other____________
Ceiling light lamps:	☐ Incandescent ☐ T-12 ☐ T-8 ☐ T-5 ☐ Compact Fluorescent Lens
Ceiling light ballast type: (check all that apply)	☐ Magnetic ☐ Electronic ☐ Dimming
Type of ceiling light control available: (check all that apply)	☐ On-off ☐ Step dimming ☐ Continuous dimming ☐ Timers ☐ Daylight sensors ☐ Occupancy sensors
Identify furniture panel colour:	☐ Light ☐ Medium ☐ Dark
Alignment of light fixtures:	☐ Directly over work surfaces ☐ At least one per workstation ☐ No alignment
Typical workstation computer screens: (check all that apply)	☐ Old deep tube CRT/VDT __________% ☐ LCD with desktop processor __________% ☐ Laptop with docking station __________% ☐ Laptop __________% ☐ Polarizing screens __________%

Task light	Fixed under bin	Desktop lamp	Articulated arm lamp
Number	_____________	_____________	_____________
Task lights ballast	☐ Magnetic ballast ☐ Electronic ballast ☐ Dimming ☐ T-12 ☐ T-8 ☐ T-5 ☐ Compact fluorescent ☐ Incandescent ☐ Halogen	☐ Magnetic ballast ☐ Electronic ballast ☐ Dimming ☐ T-12 ☐ T-8 ☐ T-5 ☐ Compact fluorescent ☐ Incandescent ☐ Halogen	☐ Magnetic ballast ☐ Electronic ballast ☐ Dimming ☐ T-12 ☐ T-8 ☐ T-5 ☐ Compact fluorescent ☐ Incandescent ☐ Halogen

Installed lighting (ceiling only) : __________ watt/sqrt

B. Selected Workstation Data Sheet: Visual Quality

WORKSTATION DATA SHEET

Space ID: **Date:**

Partial Shot

Full Shot

General Comments

Gender: ☐ Female
☐ Male
Office Type: ☐ Office Cubicle or Open Plan Workstation
☐ Shared Closed Office 2, 3, 4, or more
☐ Individual Closed Office
View: ☐ No View
☐ Seated View

Check the box if the corresponding item / condition is present in the workstation.

Visual / Lighting Stressor:

Visual / Lighting

Polarizing Screen	☐	Indirect Glare	☐
Flat Screen	☐	Fixed Task Light	☐
Plants	☐	Articulated Task Light	☐
Artifacts	☐	Undercabinet Task Lights	☐
Direct Glare	☐	Covered Windows	☐

Visual / Lighting

Light Levels	Monitor	Lux	
	Keyboard	Lux	
	Work Surface	Lux	
Glare	Direct 40 - 65%		
	Veiling Reflectance	%	
Brightness / Contrast	Monitor		
	Immediate Background	Lux	Ratio
	Minimum		
	Maximum		
	Average		
	Standard Dev.		