Strategies to Achieve Optimum Visual Quality for Maximum Occupant Satisfaction

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ABSTRACT

The variables defining visual quality in the modern workplace are evolving. A traditional focus on illuminance for paper-based tasks and brightness contrast for visual acuity are less relevant in offices with backlit computer screens and sporadic use of paper.

This research summarizes key relationships between user satisfaction, workstation lighting conditions, and the physical attributes of the work area, beginning with an overview of conditions, then the selection of variables with statistical significance, and ends with major recommendations for improving visual quality in today's work environment.

First, satisfaction levels increase when the occupants have seated view to the outside in their work area. Among 1,232 workstations in 64 office buildings, 41% had a seated view while 59% did not have a view to the outside. Providing a seated view to occupants can increase user satisfaction by 22%.

Second, upgrading the ceiling light fixture lens type could increase visual satisfaction. Workstations with the indirect lens type had higher satisfaction (61%) while the prismatic ceiling lens type showed the lowest user satisfaction (32%). The lens type of ceiling lights also plays a measurable role in both delivering light to the work surface and in managing direct and indirect glare from light fixtures. A combination of indirect light fixtures with task lights can increase user satisfaction by 17%.

Lastly, utilizing window shading devices revealed greater satisfaction with glare management. The occupants who have both external and internal shading devices showed highest satisfaction with their overall lighting.

1. Introduction

Lighting plays an important role in the quality of the indoor environment. A field study performed in the US office buildings showed that office workers' job satisfaction is highly correlated to a quality of lighting in the space such as illuminace levels and glares (Newsham et al., 2009; Veitch, Charles, Farley, & Newsham, 2007). Also, several researchers found a correlation between sustainable lighting and health. Aarås et al revealed the benefits of reducing direct and reflected glare and shadowing that can occur with direct 'downlighting' from the ceiling: a 27% reduction in headaches resulting from a shift to indirect/direct lighting (Aarås, Horgen, Bjørset, Ro, & Walsøe, 2001). In addition, the CBPD has identified twelve international case studies that indicate that improved lighting design increases individual productivity between 7-23% while reducing annual energy loads by 27-88% (CBPD, 2000; Loftness et al., 2006).

The quality of visual environment in the workplace is measured by illuminance level and luminance level. 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 (IESNA, 2011). In modern office environment, however, computer-based tasks can be the main type of work and office workers spend most of time in computer work (CBPD, 2000).

In this study, we studied visual conditions in 1,065 workstations from 64 office buildings and analyzed the relations including measured workstation's illuminance and luminance, user satisfaction with the quality of light and technical attributes of building systems such as ceiling light fixture type, ceiling lens type and seated view to outside.

2. Method and Data Analysis

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) developed the National Environmental Assessment Toolkit (NEAT) supported by General Service Administration and has collected objective and subjective data on the IEQ at individual workstations with public and private sector buildings. In this paper, we focus on visual quality findings in the field studies and will explain three different data collected using the NEAT including occupant satisfaction survey, measured IEQ, and Technical Attributes of Building Systems (TABS).

2.1. Measurements of Visual Quality in the Field

Illuminance levels on the work surface, computer monitor and keyboard are measured when the task light is on and off using Konica Minolta T-10A light meter. Once each light level is measured, the data are recorded in the NEAT cart (Figure 1). Luminance and glare levels are collected using Nikon Coolpix 5400 camera with fish eye lens. Four digital pictures are taken with different settings (combination with different aperture and exposure time). The luminance analysis uses the Photolux 2.1 which is a photometric measurement system, consisting of processing software and calibrated digital images (Photolux, 2015). Figure 2 demonstrates the luminance map as well as the statistical results generated by the software. For data analysis, we followed IESNA 10th edition's guidelines and ASHRAE measurement protocols (ASHRAE, 2010; IESNA, 2011).

Figure 1 IEQ spot measurements in the field using NEAT cart

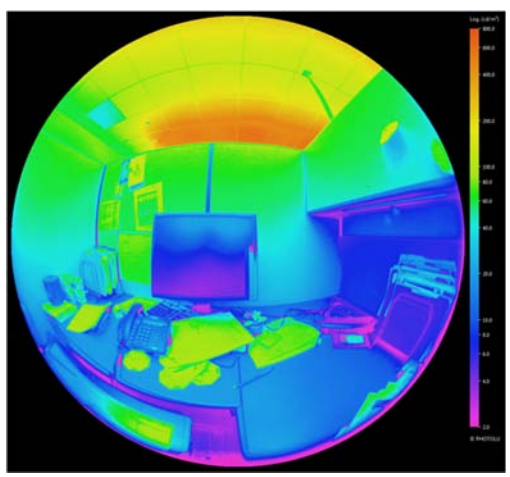


Figure 2 Luminance map generated by Photolux

2.2. Technical Attributes of Building Systems (TABS)

The CBPD at CMU team developed expert walkthrough records to ensure comparable data was recorded for the attributes of building systems that affect lighting and visual quality. The aim of recording TABS is identifying the key attributes of the building and workplace, and the quality differences that might significantly impact measured environmental conditions or individual and organizational performance.

As described earlier, three different kinds of data, namely subjective occupant response (COPE), objective building's physical attributes (TABS) and objective workstation's IEQ measurements (NEAT), were analyzed. Statistical analyses were performed using the statistical software package SAS (v.9.3) (SAS Institute, 2011). Data preparation and screening were conducted using the Baron and Kenny's method (Baron & Kenny, 1986). Multivariate regression, multiple correlation coefficient, and Pearson correlation statistical analysis of the database of 1601 workstations revealed the relationship between measured and perceived IEQ indices, interdependencies between IEQ indices and other satisfaction variables of significance. Table 1 presents the variables which were selected after data screening using correlation analysis.

Table 1 Variables for visual quality data analysis

COPE User satisfaction survey	TABS Technical Attributes of Building Systems	NEAT IEQ measurements
• Light on desk for paper-based tasks • Aesthetic appearance of your office Level of visual privacy within your office • Light for computer work • Glare on the computer screen • Direct glare from light fixtures • Direct glare from daylight • Your access to a view of outside • Quality of lighting	• 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	• 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

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 (G. Newsham & Veitch, 2009). A few questions have been added by CBPD at CMU as a result of recommendations from the GSA field study: Q11. Glare on the computer screen, Q12. Glare from electric lighting fixtures, and Q13. Glare from daylight (Aziz, Park, Loftness, & Cochran, 2012; Loftness, Aziz, Hua, Srivastava, & Yang, 2007; Park, 2013). The intention of the survey questionnaire is to understand how occupants experience their present work environments. The occupant is asked to complete a "user satisfaction questionnaire" related to today's specific environmental conditions, as compared to annual satisfaction questionnaires during the time when the workstation's IEQ measurements are recorded. This survey was distributed via paper or iPad to selected employees in the workgroup being studied. About 40% of the occupants were recruited in the survey.

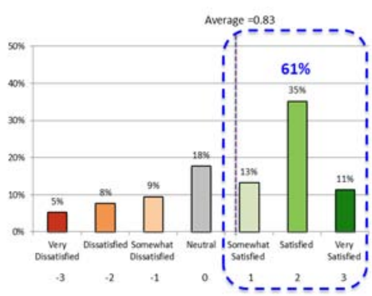
4. Results and Discussion

4.1. Field Conditions related to Visual Quality in 64 Offices

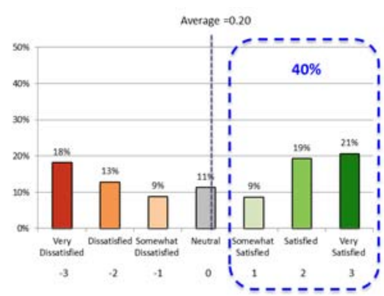
4.1.1. User Satisfaction with Visual Quality

In the short, right now questionnaire (COPE), five questions revealed aspects of user quality, seated view to outside, daylight, and lighting for paper and computer based tasks. Figure 3 shows the result of user satisfaction survey in 7-point scale. The results from 1,038 occupants in 64 office buildings revealed 61% satisfied with the overall quality of lighting in the work area, 18% neutral and 21% dissatisfied. Further review of satisfaction with lighting for paper based tasks and lighting for computer tasks revealed remarkably similar results to overall lighting satisfaction, with 61% and 66% percent satisfied respectively. The satisfactory quality of the visual environment for modern day tasks still needs to be refined. One additional variable that certainly needs to be considered is seated access to daylight and views.

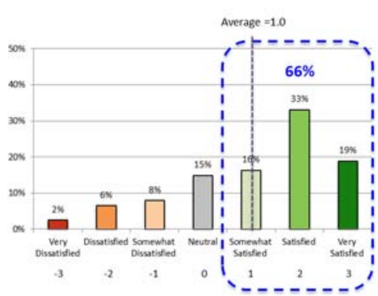
Deeper statistical analysis of these satisfaction variables revealed marginal differences between overall satisfaction and the two detailed light level questions which are 1) overall quality of lighting in your work area and 2) light level on the work surface for paper-based tasks ($p<0.05$), so the question of "overall quality of lighting in your work area" is utilized in further analysis in this paper. Where statistical significance appeared for views and daylight satisfaction relative to physical measurements or technical attributes, they are further addressed.



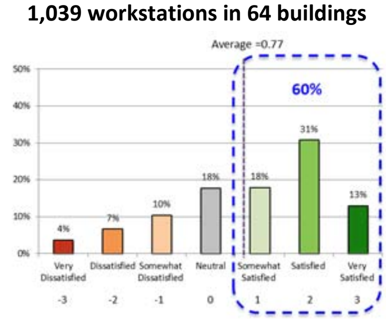
a. Quality of lighting in your work area from 1,038 workstations in 64 buildings



b. Your access to view outside from your work area from 1,039 workstations in 64 buildings



c. Light on the work surface for paper-based tasks from n=1,049 workstations in 64 buildings



d. Light for computer work from 1,033 workstations in 64 buildings

Figure 3 User satisfaction results in visual quality (4 questions)

4.1.2. Selected Visual Quality Measurements

Five field measurements were used to capture the visual quality of each workstation: light levels on the monitor, keyboard and primary paper work surface (with task lights on and off), as well as luminance ratios and unified glare ratios.

Light level variations on the 1,200 primary work surfaces in each of the 64 buildings studied are substantial, ranging from less than 50 lux to more than 1200 lux.

Multiple correlation coefficient analysis were performed for a more careful review of light levels relatives to satisfaction. The result from the scatter plot across the 1to 7 scale (n=1,245) dose shows some upward trend revealing greater satisfaction at higher levels. The occupants were generally satisfied with their overall lighting when measured light level in their workstation was greater than 210 lux.

The average workstation light level (in as-is conditions) is 617 lux (Figure 4), and 39% of workstations were below the IESNA recommended level of 500 lux for paper based tasks, suggesting that more articulated arm task lights are needed. When the task light is off, the average illuminance level is 460 lux, and over 58% of workstations were below the recommended range for paper based tasks, as shown in Figure 5.

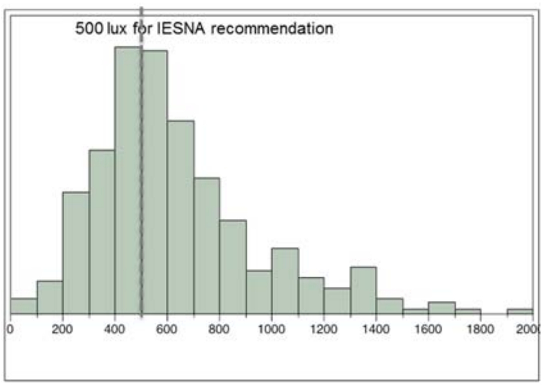


Figure 4 Light Level on work surface with task lights on (n=1,236, Average: 617.1 lux)

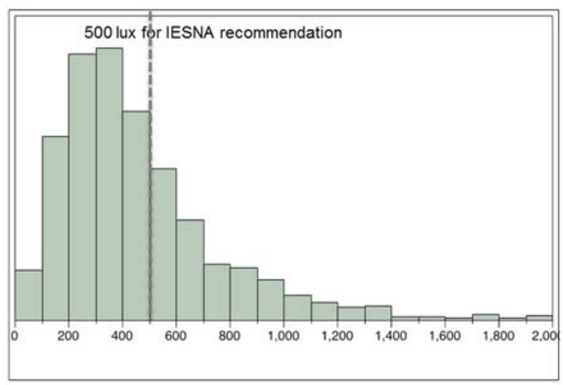


Figure 5 Light Level on work surface with task light off (n=1,236, Average: 460.5 lux)

4.1.3. Multiple technical attributes of buildings related to visual quality

Field measurements were taken on 15 variables in the TABS that contribute to visual quality, of which seven showed some level of statistical importance in early studies: ceiling fixture type, ceiling fixture shape, ceiling light lens type, ceiling light ballast type, ceiling light control, view, shades, and task light.

As further analyses are completed, a number of these variables dropped out of consideration, leaving four major technical attributes critical to user satisfaction and/or measured environmental conditions, which will be further described. It is important to note that the breadth of TABS indices collected make it impossible to catch all of the possible links in the generation of key findings. Size of zone, window quality, and level of control were consistently statistically significant ($p<0.05$). The recommendations for five variables were summarized below.

4.2. Key Findings of Visual Quality Analysis

4.2.1. Seated view & daylight = greater satisfaction + higher light levels

Satisfaction levels increase when the occupants have seated view to outside in their work area. From the distribution in seated view for 1,182 questionnaire respondents in 64 buildings, 59% of the workstations don't have a view to outside and 41% has a seated view. Seated view has significant correlation with three visual quality satisfaction questions; view to outside ($p<0.0001$), quality of lighting ($p=0.003$), and light for paper work ($p=0.028$) (Figure 6).

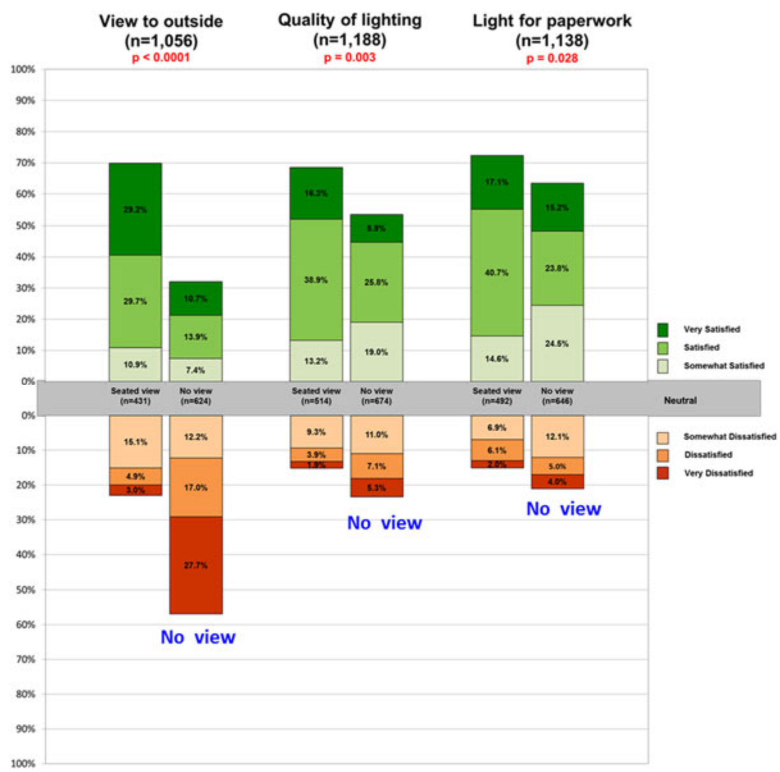


Figure 6 User satisfaction of view to outside, overall quality of lighting and light for paper work by seated view and no view workstations from 1,188 workstations in 64 buildings

4.2.1 Better ceiling fixture type = Greater satisfaction

Satisfaction levels increase when the occupants have indirect ceiling lights and individual task lights in their workstation. The TABS for ceiling light fixture was differentiated by the five categories - 2 by 2, 2 by 4, 1 by 4, I-D without hotspot, and I-D and Task light.

Table 2 shows the distribution in ceiling light fixtures for 980 questionnaire respondents in 64 buildings divided by workstations with seated view and ones without view. 64% of the offices had two by four or one by four type ceiling light fixtures. About 22% of workstations had indirect celling lights, and 5% of offices had indirect light fixtures.

Table 2 Distribution in ceiling light fixture for 980 Questionnaire respondents in 64 buildings (divided seated view and no view workstation locations)

	2 by 2	**2 by 4**	**1 by 4**	**I-D without hotspot**	**I-D and Task light**
Seated view	102 (83%)	178 (54%)	44 (14%)	86 (51%)	19 (36%)
No view	21 (17%)	150 (46%)	264 (86%)	82 (49%)	34 (64%)
Total	123	328	308	168	53

Satisfaction with lighting quality increased with the combination of indirect celling 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, 80% of users were satisfied while about 55% of occupants were dissatisfied with two by two ceiling light fixtures as shown in Figure 7. The effect of the ceiling light fixture 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).

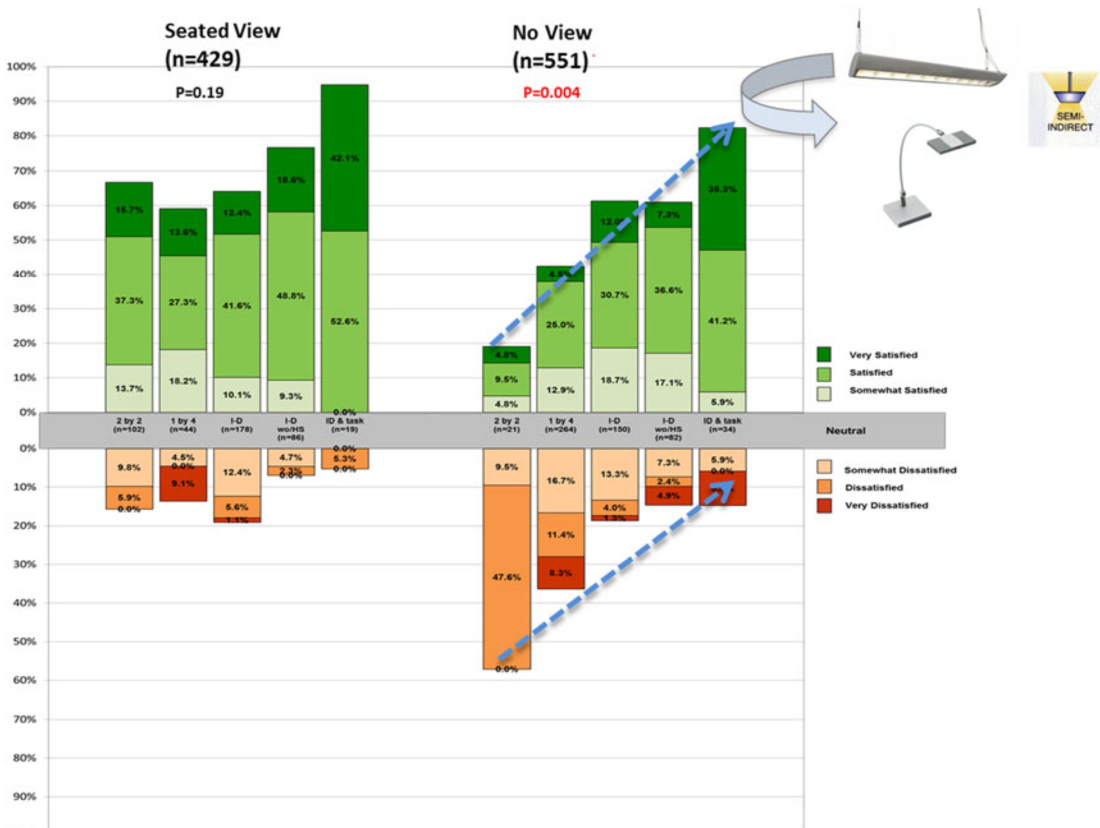


Figure 7 Visual Satisfaction by ceiling light fixture by Seated view and No view workstations (n=980)

4.2.3. Ceiling fixture lens type = greater satisfaction + higher light levels + glare management

The lens type of ceiling lights plays a measurable role in both delivering light to the work surface and in managing direct and indirect glare from light fixtures. Statistical analysis revealed that lens type was significant for open plan workstation areas (n=683). While there was not statistical variation in satisfaction for occupants with seated views, satisfaction with overall lighting quality increased when the ‘covers’ on light fixtures were no longer flush prismatic lenses or large cell parabolic louvers, both of which can contribute to direct and indirect glare from bright sources (Figure 8, $p<0.01$).

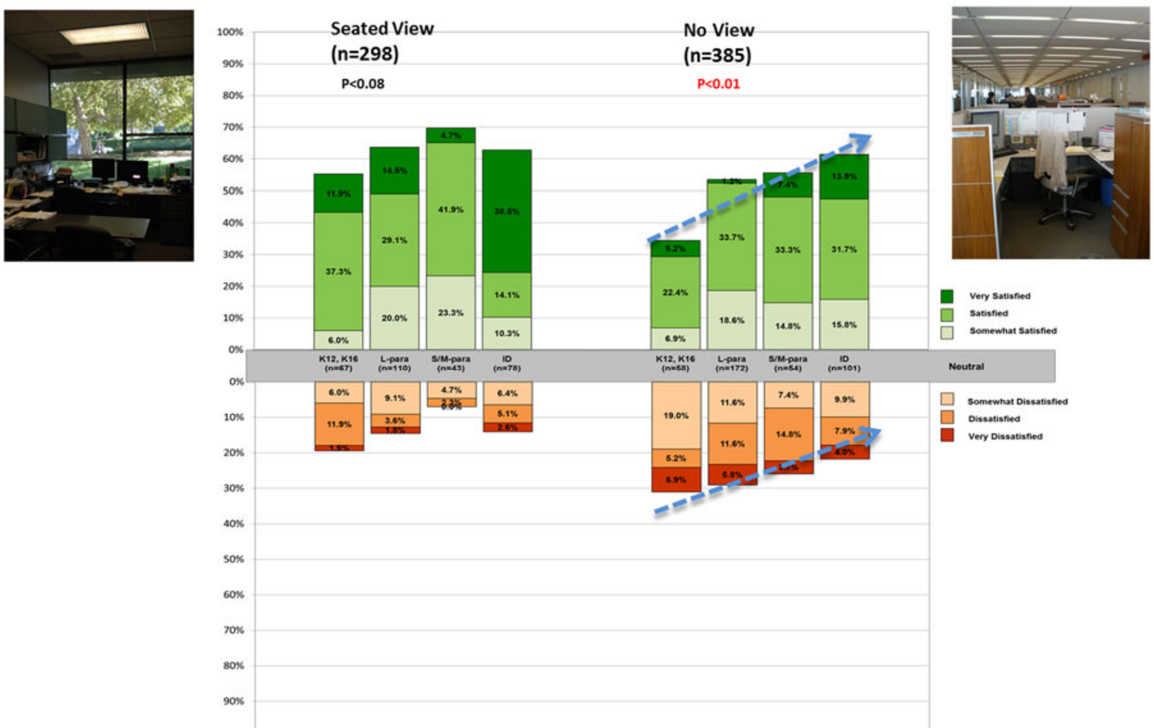


Figure 8 Visual Satisfaction by ceiling lens type by Seated view and No view workstations in perimeter workstation (n=683)

Upgrading ceiling lens type can increase user satisfaction on quality of lighting in a work area. 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 and 14 % of workstations with medium parabolic and 26% had indirect ceiling lens from 683 open-plan workstations in 64 buildings (Table 3).

Table 3 Distribution in ceiling lens type for 683 Questionnaire respondents in 64 buildings (divided seated view and no view workstation locations)

	Prismatic	**Large Parabolic**	**Small or Medium Parabolic**	**Indirect**
Seated view	67 (54%)	110 (39%)	37 (38%)	78 (44%)
No veiw	58 (46%)	172 (61%)	60 (62%)	101(56%)
Total	*125 (18%)*	*282 (41%)*	*97 (14%)*	*179 (26%)*

User satisfaction for overall lighting increased with indirect ceiling lens type in the workstations with no seated views ($p<0.01$). There was a statistical difference with ceiling lens type: on average, indirect lens type had higher satisfaction (61%), while large parabolic and medium/small parabolic lens types (52%) showed lower visual satisfaction ($p<0.01$). Especially, the prismatic celling lens type showed lowest user satisfaction (32%). The effect of the ceiling lens type was only critical in the workstations in the no seated view workstations ($p=0.01$) and had no strong relation in the seated view workstations ($p=0.08$).

4.2.4. Window shading devices = greater satisfaction + glare management

Shading type can affect user satisfaction. The visual TABS for shading type was differentiated by the five categories. The effect of the shading type was only critical in the workstations with seated views ($p=0.03$), and had no strong relation in the no seated view workstations ($p>0.05$). Table 4 shows the distribution in shading type for 995 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 5% of workstations (n=54) had both external and internal shading devices in their work area.

Table 4 Distribution in shading type for 997 Questionnaire respondents in 64 buildings (divided seated view and no view workstation locations)

	No control	**Roll down**	**Vertical**	**Horizontal**	**External & Internal**
Seated view	23 (43%)	68 (75%)	226 (61%)	142 (31%)	22 (73%)
No veiw	31(57%)	23 (23%)	144 (39%)	310 (69%)	8 (8%)
Total	*54 (5%)*	*91 (9%)*	*370 (37%)*	*452 (45%)*	*30 (3%)*

Overall, the occupants who have seated view showed high satisfaction on overall visual quality in their work area. Especially, when they have more controls such as external and internal devices together, about 90% of responses were satisfied with their visual environmental in their work area (Figure 9).

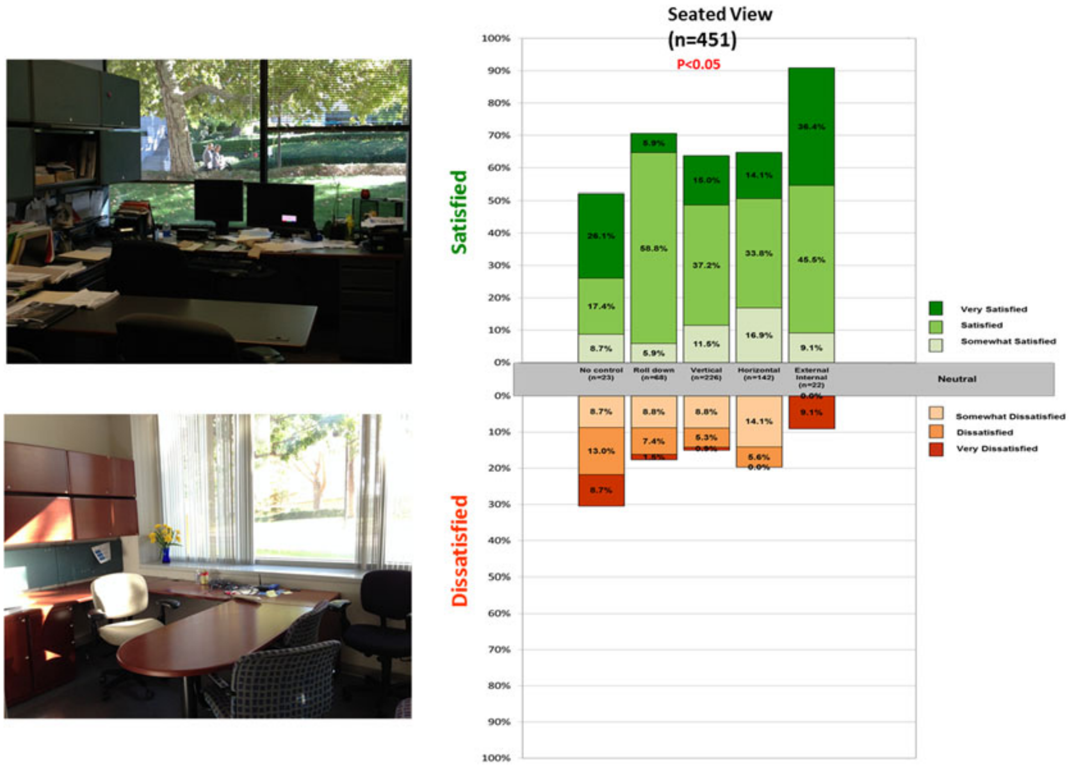


Figure 9 Visual satisfaction by shading type in seated view workstations (n=451)

4.2.5. Managing illuminance on the work surface = greater satisfaction + code compliance

The illuminance levels from 1,236 workstations in 64 buildings revealed that the average workstation light level (in as-is conditions) is 617 lux, and 39% of workstations were above the Illuminating Engineering Society of North America (IESNA) recommended level of 500 lux. When the task light is off, the average illuminance level is 460 lux, and still 58% of workstations were over the recommended range.

The user satisfaction survey result from 1,245 workstations in 64 buildings shows that there is no strong relation between measured illuminance level and user satisfaction ($p>0.05$). The occupants were satisfied with their overall lighting conditions when measured light level in their workstation was greater than 210 lux.

5. Conclusions

5.1. Humans are effective sensors

Combining occupant responses with key IEQ attributes can provide insight that is comparable to complex field instrumentation. Key IEQ indices can be defined using occupant survey responses and the detailed indices and questions summarized in Table 5. For example, asking occupants, “Overall quality of lighting in your work area?” can inform whether room lighting condition is within the comfort range or not.

Table 5 IEQ measurements which can be defined using survey questions

IEQ Criteria	Indices	Survey Questions
Visual Quality	• Luminance ratio • Illuminance level	Q. Overall quality of lighting in your work area

5.2. Occupant satisfaction can inform design decisions

Occupant satisfaction can help inform design decisions. Among technical attributes of building systems, highlighted parameters were critical for user satisfaction and can guide a design decision. In visual quality, for example, having a seated view, better ceiling lens type, better ceiling light fixture, and external and internal shading devices are recommended.

Table 6 Technical attributes of building systems which significantly impacted user satisfaction

IEQ Criteria	Technical attributes of building systems	User Satisfaction Questions
Visual Quality	Seated View Ceiling Lens Type Ceiling Light Fixture Shading Type	Q. Overall quality of lighting in your work area Q. Light for paper-based work

5.3. Occupants redefine comfort thresholds

Occupant satisfaction survey response can be used to redefine user comfort thresholds. Given our dataset, using 1,601 workstation's IEQ measurements and user satisfaction survey responses from 64 buildings, IEQ comfort thresholds for highest building occupant satisfaction were redefined as shown in Table 7.

Table 7 Redefined thresholds for user comfort derived from given US average buildings

IEQ Criteria	IEQ measurements	Thresholds for highest satisfaction (given US average bldgs.)	Standards (ASHRAE 55)
Visual Quality	Illuminance on monitor	290 lux	500 lux (IESNA 2011)
	Illuminance on keyboard	400 lux	500 lux (IESNA 2011)
	Illuminance on work surface	400 lux	500 lux (IESNA 2011)

References

Aarås, A., Horgen, G., Bjørset, H.-H., Ro, O., & Walsøe, H. (2001). Musculoskeletal, visual and psychosocial stress in VDU operators before and after multidisciplinary ergonomic interventions. A 6 years prospective study—Part II. *Applied ergonomics, 32*(6), 559-571.

ASHRAE. (2010). *Performance Measurement Protocols for Commercial Buildings*: American Society of Heating, Refrigerating and Air Conditioning Engineers

Aziz, A., Park, J., Loftness, V., & Cochran, E. (2012). Field measurement Protocols for Evaluating Indoor Environmental Quality and User Satisfaction in Relation to Energy Efficiency *U.S. DOE* (Vol.). The Energy Efficient Buildings Hub, Department of Energy

Baron, R., & Kenny, D. (1986). The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of personality and social psychology, 51*(6), 1173.

CBPD. (2000). BUILDING INVESTMENT DECISION SUPPORT (BIDS™), Center for Building Performance and Diagnostics (CBPD), Carnegie Mellon University. *ABSIC Project# 00-2 Final Report, 2001*.

IESNA. (2011). *The IESNA Lighting Handbook 10th Edition* (K. H. David DiLaura, Richard Mistrick, Gary Steffy Ed.): Illuminating Engineering Society of North America.

Loftness, V., Aziz, A., Hua, Y., Srivastava, V., & Yang, X. (2007). *GSA WP 20•20 Environmental Quality Report: Kluczynski Federal Building, Chicago, IL. Before- and After-renovation Comparison* (Vol. null).

Loftness, V., Hartkopf, V., Lam, K. P., Snyder, M., Hua, Y., Gu, Y., Yang, X. (2006). *Sustainability and health are integral goals for the built environment.* Paper presented at the Healthy Buildings: Creating a Healthy Environment for People, Proceedings of HB2006 International Conference, Lisbon, Portugal.

Newsham, G., Brand, J., Donnelly, C., Veitch, J., Aries, M., & Charles, K. (2009). Linking indoor environment conditions to job satisfaction: a field study. *Building Research & Information, 37*(2), 129-147. doi:10.1080/09613210802710298

Newsham, G., & Veitch, J. (2009). *National Research Council(NRC) Cost-effective Open-plan Environments Project (COPE).*

Park, J. (2013). *Post-occupancy evaluation for energy conservation, superior IEQ & increased occupant satisfaction.* Paper presented at the IFMA's World Workplace 2013, Philadelphia, PA.

Photolux. (2015). Retrieved from http://www.photolux-luminance.com

SAS Institute, I. (2011). SAS® 9.3: Software. SAS Institute, Inc. Cary, NC, http://support.sas.com/software/93/.

Veitch, J., Charles, K., Farley, K., & Newsham, G. (2007). A model of satisfaction with open-plan office conditions: COPE field findings. *Journal of Environmental Psychology, 27*(3), 177-189. doi:http://dx.doi.org/10.1016/j.jenvp.2007.04.002