

# Worker Reactions to Electrochromic and Low e Glass Office Windows

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## Abstract

Occupant surveys about the daylight and the visual environment effects of work, satisfaction, health and well-being, were conducted in 5 office buildings with electrochromic glass (n=268) and 2 office buildings with low-e glass (n=44). Online surveys were administered to volunteer participants. Results showed that subjective reports of eyestrain, headaches, lighting quality satisfaction, window glass lighting quality, and alertness were significantly better for the electrochromic glass buildings. No significant differences between building types were found for daylight glare, daylight quality, mood, energy levels, health and well-being, self-rated productivity, and work quality. Findings show that electrochromic glass can improve indoor light quality that benefits occupant comfort and wellness.

**Keywords:** Electrochromic Glass; Office Windows; Daylight; Office Lighting; Eyestrain; Visual Comfort; Work Quality

## Introduction

Current sustainable building ratings systems, such as LEED or WELL, reward building designs that use windows to facilitate daylight penetration into the buildings. In the LEED system, windows in regularly occupied areas of a building are important for daylight exposure and to give occupants external views that provide a connection between the indoors and the outdoors [1,2]. The WELL building rating system, Version 2, states that "Light is the main driver of the visual and circadian systems" and it favors projects that "design spaces to integrate daylight into indoor environments so that daylight may be used for visual tasks along with electric lighting [3,4]. It also provides individuals with a connection to outdoor spaces through view windows" (WELL v2, CONCEPTS / LIGHT / FEATURE L05, Enhanced Daylight Access, 2018). Similarly, Fitwel (2018) awards points for buildings that "Provide natural daylight in a majority of workspace" and "Provide views of nature to the outside from a majority of workstations." Fitwel recognizes that windows can be a

source of glare so also awards credit for providing "Operable shading of all workspace windows."

Windows allow daylight to enter buildings and daylight plays an important role in human health. Daylight improves vitamin D synthesis and synchronizes circadian rhythms [5,6]. Window views to the outdoors can improve health, especially where views are of natural scenes with trees and vegetation [7]. Looking through a window to a view of nature reduces nervousness/anxiety levels compared to a view to a cityscape or no window view [8]. Heschong [9] showed that performance in a call center was 6-7% faster when workers had a window view. Leather, et al. [10] found that access to daylight can increase job satisfaction and outdoor views can reduce job stress. Perhaps not surprisingly, Aries found that people overwhelmingly prefer working near windows [11]. However, daylight intensity through windows varies throughout the day and from day to day throughout the year. Also, window orientation affects daylight penetration and bright daylight can create direct and

reflected glare problems for occupants, especially those sitting at the south and the west facing façades [12].

Some 50% of daylight comprises of infrared wave lengths (heat). Sitting close to a window on a hot and sunny day can be both visually uncomfortable from glare, and thermally uncomfortable from solar heat gain. Glare can also increase symptoms of computer vision syndrome (CVS), characterized by (symptoms of eyestrain, tired eyes, irritation, redness, blurred vision, and double vision among office workers, especially those near to windows [13,14]. To combat solar heat and glare, low emissivity (low-e) glass coatings are often used in for commercial building façades to reduce solar heat gains and/or losses through windows, and low-e glass can be tinted to reduce glare. However, low-e glass still allows some infrared light (solar heat gain) and it has a fixed light transmittance. To mitigate these problems internal or external blinds often

are used, but the deployment of blinds diminishes or eliminates access to outside views.

Unlike low-e glass, electrochromic glass (EC) is electrically controlled to change its light transmittance, from a clear state, with almost 60% light transmittance, to varying darker states (down to only 1% light transmittance) to reduce daylight glare and solar heat gain without blocking a view to the outside (Figure 1). Infrared light (solar heat) comprises wavelengths from 0.70-1 micron, and as this figure shows, these wavelengths are filtered out in tint states 3 and 4, which save on the usage of air-conditioning [15]. In these tint states, most of the transmitted visible light is in the blue wavelengths (0.45-0.49 microns) and green wavelengths (0.49-0.57 microns). In all tint states, there is a view through the electrochromic glass, but the greater the tint state, the bluer the appearance of the window.

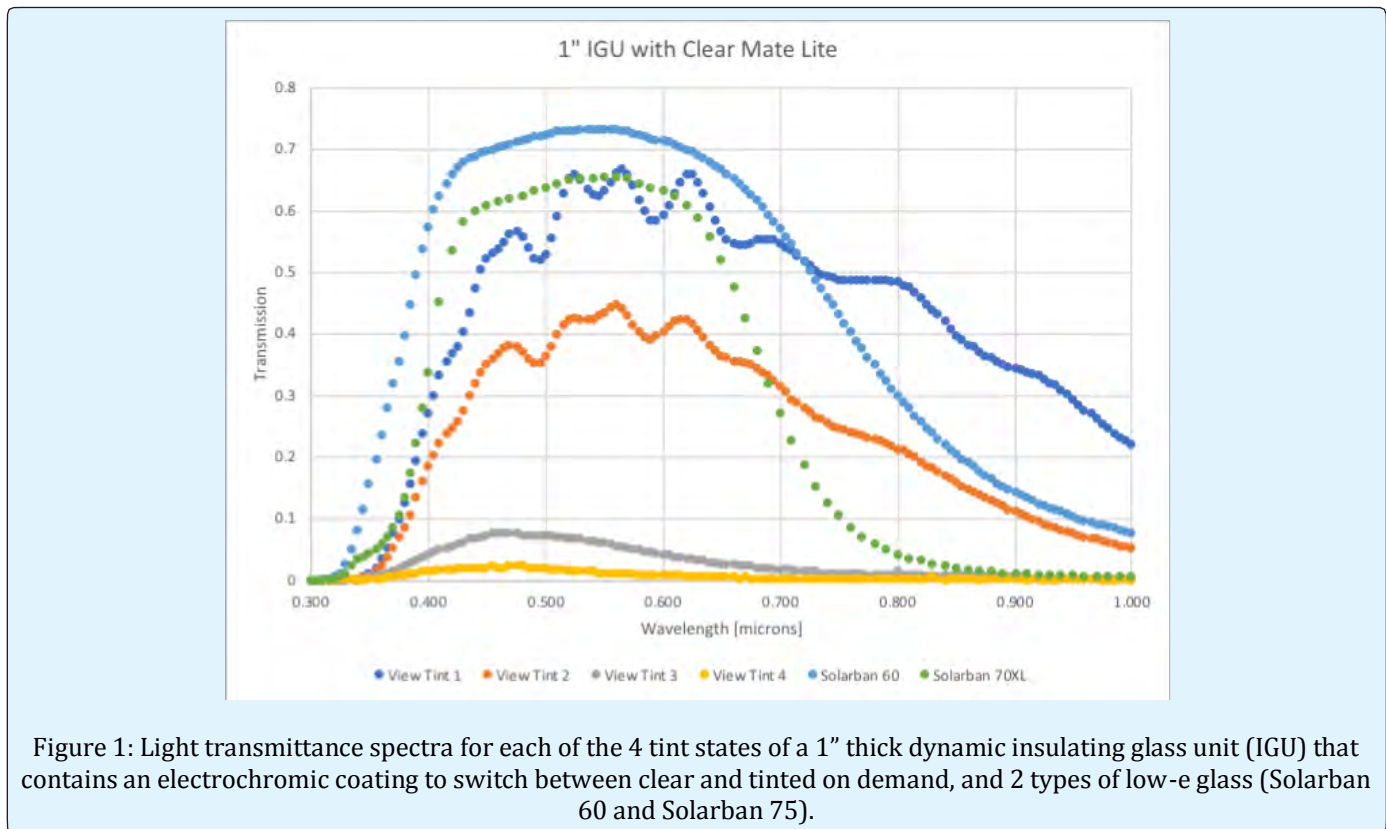


Figure 1: Light transmittance spectra for each of the 4 tint states of a 1" thick dynamic insulating glass unit (IGU) that contains an electrochromic coating to switch between clear and tinted on demand, and 2 types of low-e glass (Solarban 60 and Solarban 75).

Intrinsically photosensitive retinal ganglion cells (ipRGCs) respond to blue light, with peak absorption at 0.48 microns, and they help to synchronizing circadian rhythms to the 24-hour light/dark cycle and they have involvement in the pupillary light reflex response as light levels change [16]. Mills, Tomkins, and Schlangen [17] found significantly less fatigue and daytime sleepiness, improved alertness and work performance, greater

vitality and better mental health in a shift-working call center with high correlated color temperature (17000 K) fluorescent lights with greater blue light wavelengths that can stimulate ipRGCs. There is a growing body of evidence that blue light can improve mood, alertness, memory, cognitive performance and aids in coping with any effect of a post-lunch dip on the EEG and in performance [18-23]. Hedge and Nou [24] found that electrochromic glass

also may improve worker visual comfort and satisfaction, and reduce symptoms associated with CVS.

The present study compared reactions of office workers to their visual environment in buildings with façades with either traditional low-e glass (LeG) or electrochromic glass (EC). Given the evidence reviewed we hypothesized that in office buildings with EC, opinions of the visual environment, lighting satisfaction, lighting performance, CVS, alertness, and sleep quality will be better than for workers in office buildings with LeG.

## Methods

### Survey Samples

The study sample comprised a 268 volunteer office workers was surveyed from in 5 office buildings with EC and 45 volunteer office workers in 2 buildings with LeG. All office buildings were in North America (Salt Lake City, Utah; Gainesville, Florida; Seattle, Washington; Charleston, West Virginia; and Toronto, Canada) (Table 1).

Site	Area (sqft)	Participants	Est. Salary with Benefits
Ontario, CA	37,000	50	\$87,500
Boone, NC	18,000	54	\$112,000
Gainesville, FL	15,500	105	\$93,000
SLC, UT	252,000	25	\$81,250
Seattle, WA	89,000	35	\$70,000

Table 1: Summary of the sample characteristics.

### Survey Questionnaires

An online survey questionnaire (Google Forms) was designed to evaluate occupant responses for the following factors: Comfort, Satisfaction, Performance, Productivity, Alertness, Sleep, Health, and Well-being. Each participating company was allowed make minor modifications to their survey, but not the core questions. All surveys were administered electronically over the internet (Google Docs) in September 2017. Respondents were given 2 weeks to complete their survey.

## Statistical Analysis

All survey data was computer coded and analyzed using multivariate statistical software (PSPP 1.01) to compare response for respondents in the EC and LeG buildings. The criterion of significance for all statistical tests was  $p < 0.05$ .

## Results

### Sample Demographics

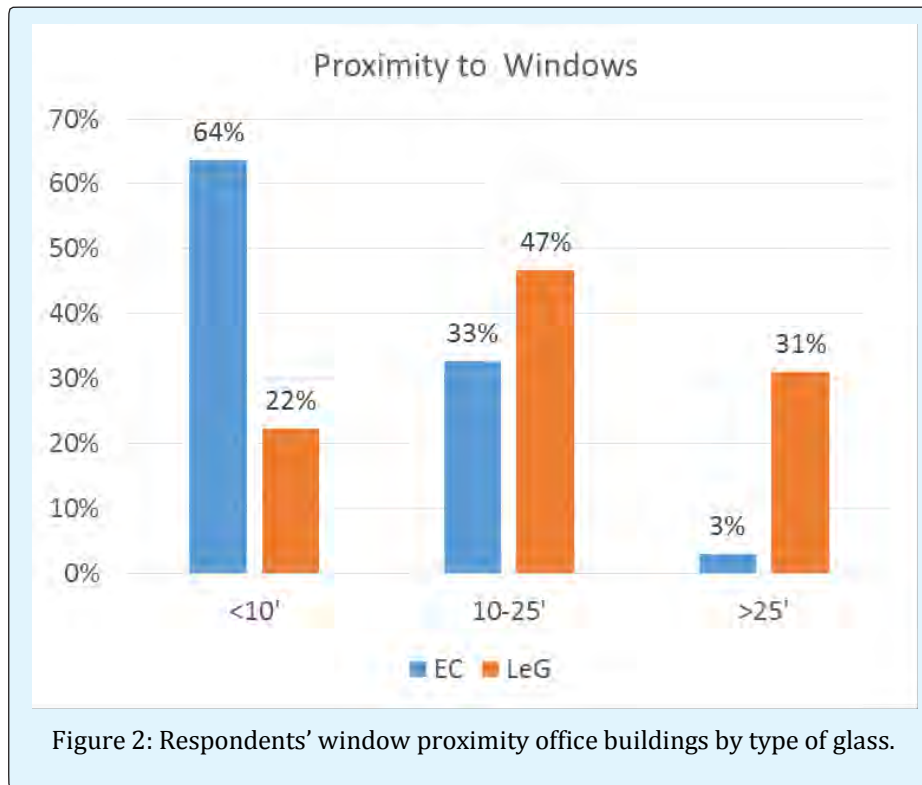
There was no significant difference in the distribution of gender for respondents and 47.4% were male in the EC offices and 29.5% were male in the LeG offices. There was no significant difference in the tenure profile of respondents and most respondents had worked in their building for one year or less. (67.8% in EC offices; 86.6% in LeG offices). Most respondents (94.6%) had worked in various other types of office buildings prior to the survey. There was no significant difference in respondent's use of corrective lens and 39.0% in the EC offices and 43.6% in the LeG offices wore no corrective lens. There was no significant difference in the ages of respondents in the EC and LeG samples (Table 2).

Age (years)	EC (n=266)	LeG (n=44)
<=20-30	37.6%	38.7%
31-40	27.8%	25.0%
41-50	13.5%	15.9%
51-60	21.0%	20.4%

Table 2: Respondent ages in the EC and LeG buildings.

### Window Proximity

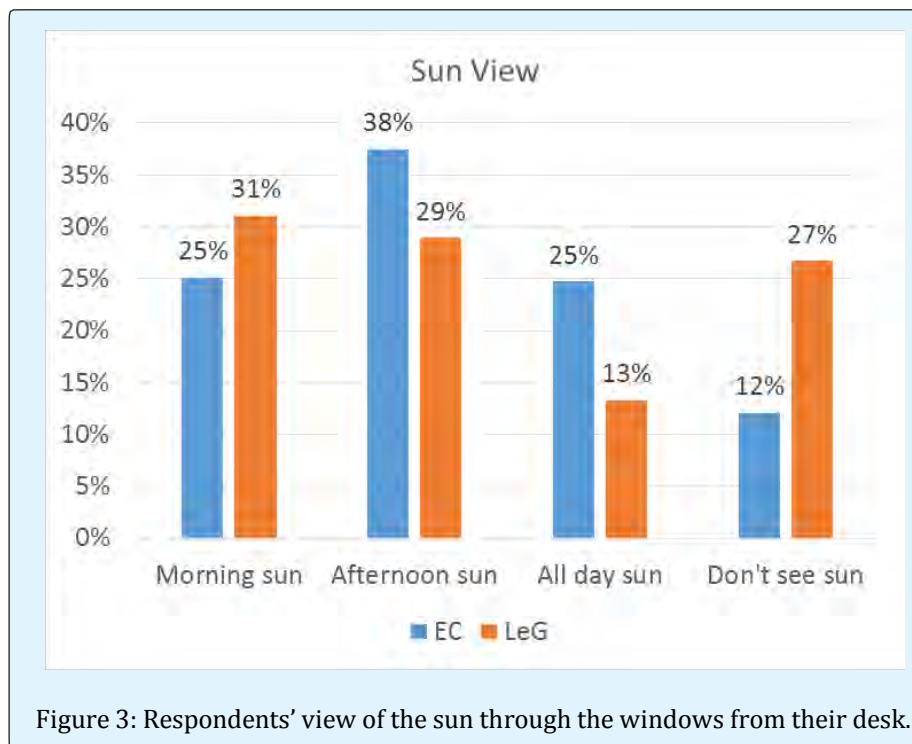
EC reduces the solar gain of heat through windows and consequently more people should be able to comfortably sit closer to the windows. As predicted, there was a significant difference in window proximity between EC and LeG buildings ( $\chi^2(3, N=312) = 57.180, p = 0.000, \phi = .394$ ), and three times more workers in the EC buildings sat within 10 feet of a window compared to the LeG buildings (Figure 2).



### Sun View

There was a significant difference between buildings with the EC and those with LeG ( $\chi^2(4, N=312) = 10.320, p = 0.035, \phi = .179$ ), and twice as many workers in the LeG

buildings than in the EC buildings said that they don't see any sun through the windows from their office desk (Figure 3).



### Daylight Quality

Respondents were asked to rate the quality (brightness, color) of the daylight in their office, and there was a significant difference in ratings of daylight quality between the EC and LeG buildings ( $\chi^2 (3, N=311) =$

18.281,  $p = 0.000$   $\phi = .236$ ), and as shown in Figure 4, more respondents in the EC buildings said that daylight was 'excellent' or 'really good' (70%) than compared with those in the LeG buildings (39%) (Figure 4).

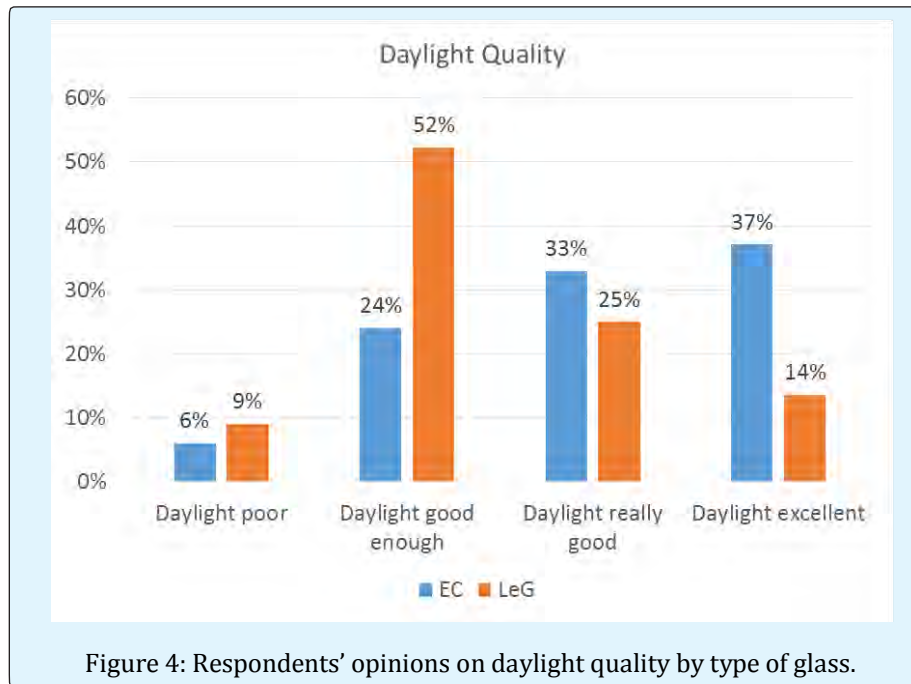


Figure 4: Respondents' opinions on daylight quality by type of glass.

### Overall Lighting Quality

There was a significant difference in ratings of overall lighting quality between buildings with the EC and those with LeG ( $\chi^2 (5, N=310) = 13.777$ ,  $p = 0.017$   $\phi = .206$ ), and

almost three times more respondents in the EC buildings than in the LeG buildings said that their overall lighting quality was 'excellent' (Figure 5).

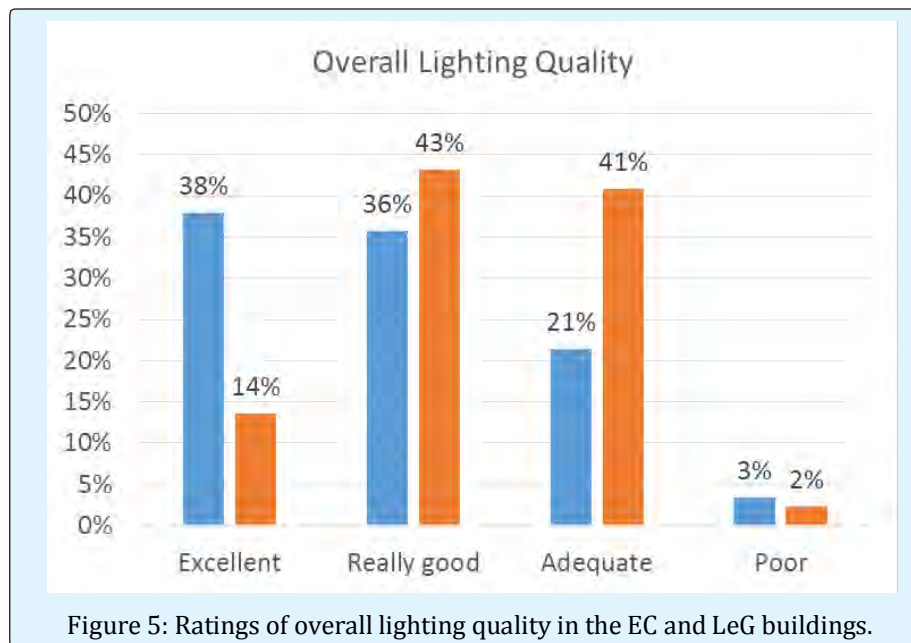


Figure 5: Ratings of overall lighting quality in the EC and LeG buildings.



### Office Lighting and Eyestrain

There was a significant difference in the frequency of experiencing eyestrain between buildings with the EC and those with LeG ( $\chi^2 (4, N=311) = 26.947, p = 0.000 \phi =$

.282), and more workers in the LeG buildings than in the EC buildings said that they experience eyestrain (Figure 6).

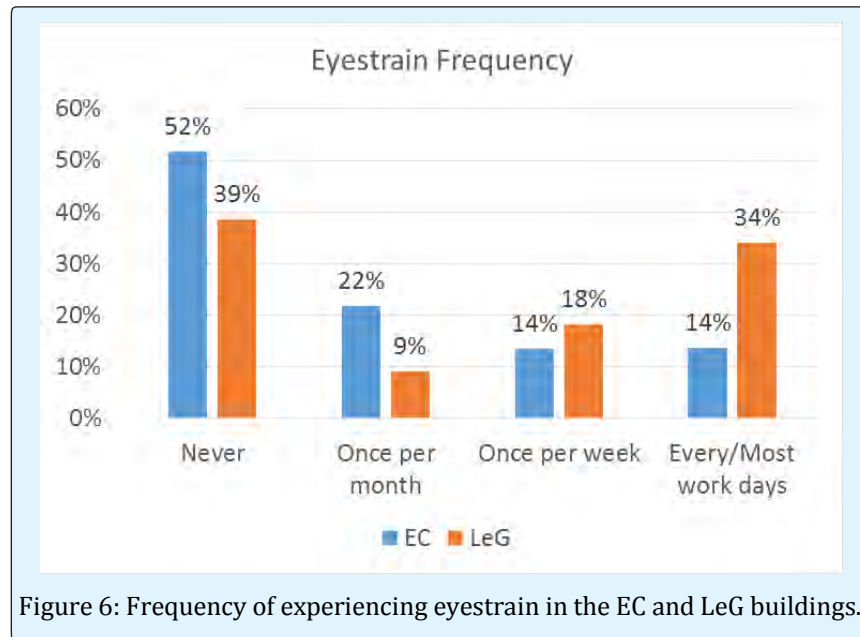


Figure 6: Frequency of experiencing eyestrain in the EC and LeG buildings.

### Office Lighting and Headaches

There was a significant difference in the frequency of experiencing headaches ( $\chi^2 (4, N=311) = 18.591, p = 0.001 \phi = .238$ ), and more respondents in the EC buildings

in the LeG buildings said that they never experience headaches (Figure 7).

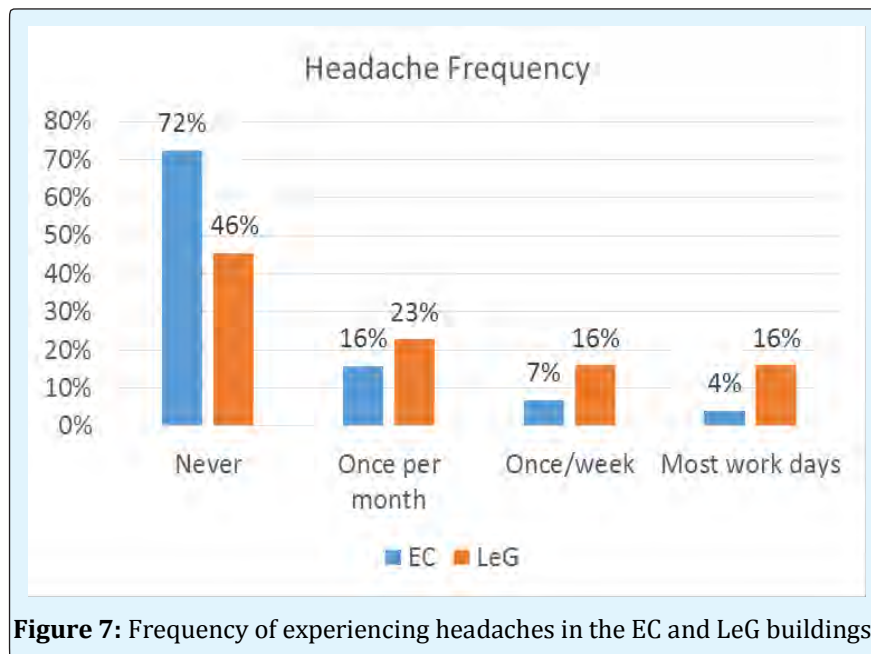


Figure 7: Frequency of experiencing headaches in the EC and LeG buildings.

### Lighting Quality and Satisfaction

Satisfaction with the quality of the lighting (daylight + artificial light) in the office was significantly different between the EC buildings and those with LeG ( $\chi^2 (4,$

$N=310) = 15.864, p = 0.003 \phi = .221$ ), and many more respondents in the EC buildings compared with those in the LeG buildings said that they were satisfied with their lighting quality (Figure 8).

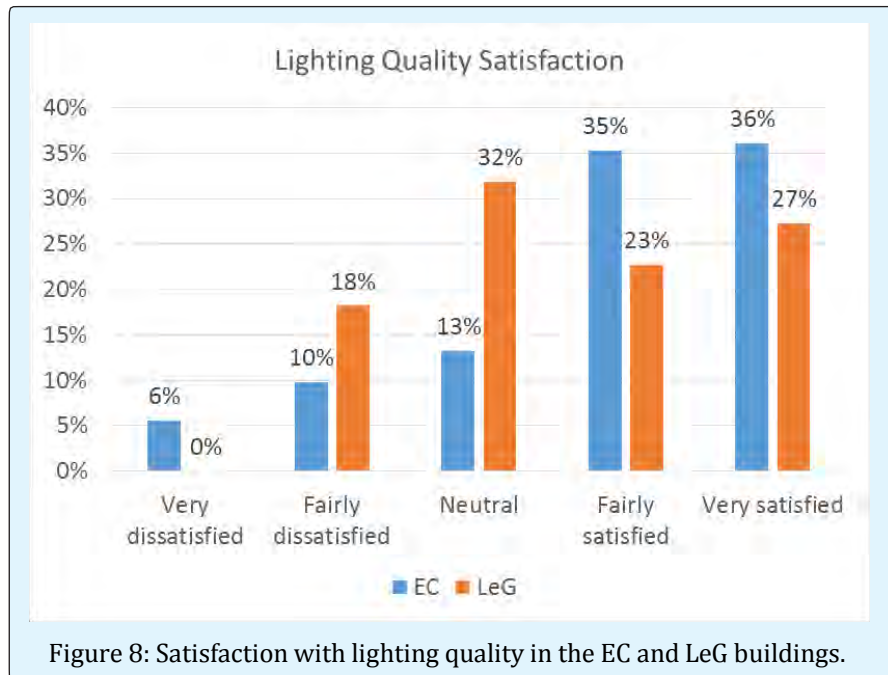


Figure 8: Satisfaction with lighting quality in the EC and LeG buildings.

### Opinion of Window Glass and Lighting Quality

Opinions on the window glass and lighting quality were significantly different between the EC and LeG buildings ( $\chi^2 (2, N=310) = 23.643, p = 0.000 \phi = .266$ ), and more

respondents in the EC buildings than in the LeG buildings said that the glass improves the lighting quality (Figure 9).

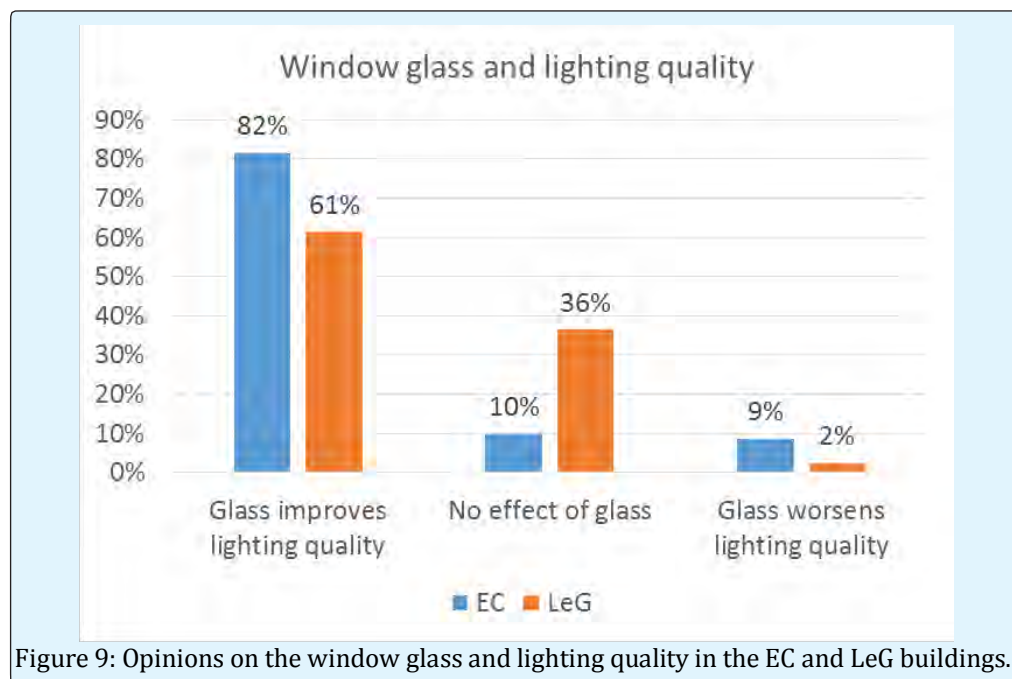
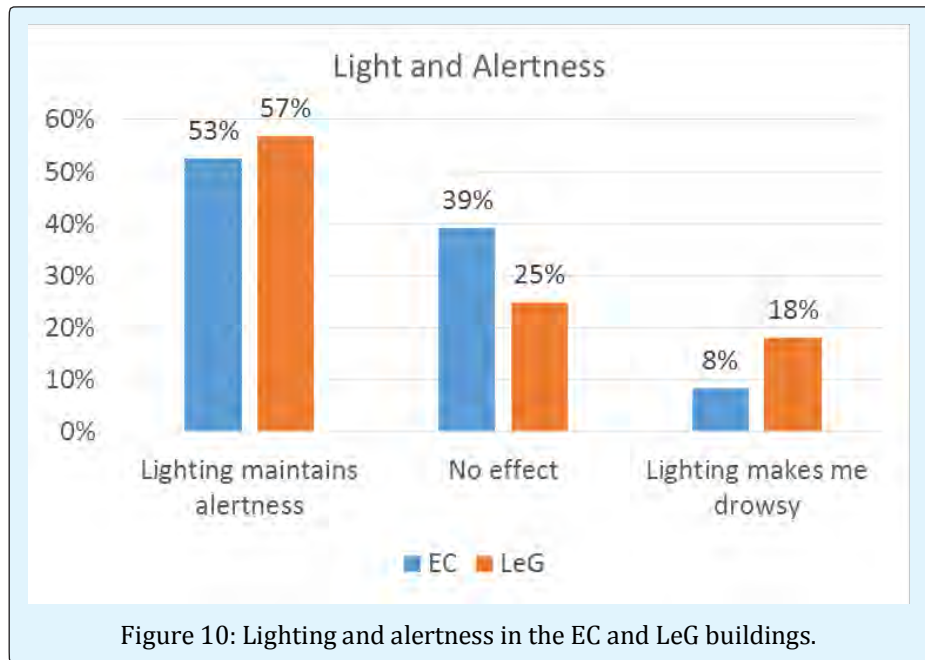


Figure 9: Opinions on the window glass and lighting quality in the EC and LeG buildings.

## Lighting and Alertness

As predicted, the effects of lighting on alertness was significantly different between the EC and LeG buildings ( $\chi^2(2, N=310) = 5.979, p = 0.050, \phi = .138$ ), and fewer

workers in the EC buildings said that the lighting makes them feel drowsy compared with those in the LeG buildings (Figure 10).



## Daylight Glare

There was no significant difference between EC and LeG buildings in experiences of daylight glare. As shown in Table 3, only a small minority of respondents experienced daylight glare daily in the EC and LeG buildings.

	Daylight glare frequency				
	Never	1-2 month	1-2 week	Most days	Every day
EC (n=267)	49.8%	19.5%	14.2%	10.9%	5.6%
LeG (n=44)	61.4%	4.5%	13.6%	15.9%	4.5%

Table 3: Respondents' reports of daylight glare by type of glass.

## Office Windows, Lighting Quality, Window Proximity and Productivity

There was no significant difference in responses between buildings with the EC and those with LeG, and 65% of respondents in the EC buildings and 57% of respondents in the LeG buildings said that the windows improve lighting quality and their productivity (see Table 4).

Windows-lighting quality-productivity	EC (n=265)	LeG (n=44)
Windows improve lighting and productivity a lot	35.8%	40.9%
Windows improve lighting and productivity a little	29.4%	15.9%
Windows only improve lighting	20.8%	27.3%
No effect of windows	9.1%	11.4%
Windows don't affect lighting/little less productivity	3.8%	2.3%
Windows don't affect lighting/lot less productivity	1.1%	2.3%

Table 4: Effects of windows and lighting quality on productivity in the EC and LeG buildings.

There was no significant difference in percentage productivity responses between buildings with the EC and those with LeG. As shown in table 5, around the same percentage of respondents said that the windows and office lighting improve productivity in the EC buildings (62.5%) and in the LeG buildings (50.0%). For the effects of windows and office lighting the mean percentage productivity ( $\pm$  S.E.) was  $1.75\% \pm 0.14\%$  in the EC buildings and  $1.30\% \pm 0.40\%$  for the LeG buildings.



	Percent Productivity										
	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
EC (n=265)	0.02	0.4%	1.9%	1.5%	2.6%	29.1%	7.9%	14.3%	14.7%	11.3%	14.3%
LeG (n=44)	0.02	2.3%	6.8%	2.3%	2.3%	34.1%	2.3%	6.8%	18.2%	6.8%	15.9%

Table 5: Effects of windows and lighting quality on percent productivity in the EC and LeG buildings.

There was no significant difference between the EC and LeG buildings for the effect of window proximity on productivity, as shown in Table 6.

Mean % productivity		
Window proximity	EC	LeG
<10'	1.95	2.00
10-25'	1.41	1.05
>25'	1.43	1.14
Interior office	1.00	0.00

Table 6: Effects of windows proximity on percent productivity in the EC and LeG buildings.

### Daylight Quality and Mood

There was no significant difference in responses between buildings with the EC and those with LeG. As shown in Table 7, around the same percentage of respondents said that the daylight quality was pleasant and made them happier in the EC buildings (84.1%) and in the LeG buildings (88.6%).

Daylight and mood	EC (n=264)	LeG (n=44)
Daylight pleasant/lot happier	50.8%	47.7%
Daylight pleasant/little happier	33.3%	40.9%
No effect of daylight on mood	12.1%	9.1%
Daylight annoying/little worse mood	3.4%	0.0%
Daylight annoying/lot worse mood	0.4%	2.3%

Table 7: Effects of daylight quality on mood in the EC and LeG buildings.

### Daylight Quality, Health and Wellbeing

There was no significant difference in responses between buildings with the EC and those with LeG. As shown in table 8, around the same percentage of

respondents said that the daylight improves health in the EC buildings (72.0%) and in the LeG buildings (85.8%).

Daylight-health-wellbeing	EC (n=247)	LeG (n=44)
Daylight improves health a lot	34.5%	38.6%
Daylight improves health a little	37.5%	47.7%
No effect of daylight	24.3%	11.4%
Daylight worsens health a little	3.7%	2.3%

Table 8: Effects of daylight quality on health and wellbeing in the EC and LeG buildings.

### Daylight Quality and Energy

There was no significant difference in responses between buildings with the EC and those with LeG. As shown in table 9, most respondents said that the daylight increases their energy level in the EC buildings (67.3%) and in the LeG buildings (68.2%).

Daylight - energy level	EC (n=266)	LeG (n=44)
Lot more energy	23.3%	25.0%
Little more energy	44.0%	43.2%
No effect on energy	26.7%	25.0%
Little less energy	5.3%	4.5%
Lot less energy	0.8%	2.3%

Table 9: Daylight quality and energy level in the EC and LeG buildings.

### Daylight Quality and Work Quality

There was no significant difference in responses between buildings with the EC and those with LeG. As shown in table 10, most respondents said that the daylight quality improves their work quality in the EC buildings (57.5%) and in the LeG buildings (72.8%).

Daylight and work quality	EC (n=266)	LeG (n=44)%
Work quality improved a lot	18.4%	27.3%
Work quality improved a little	39.1%	45.5%
No effect	39.1%	22.7%
Work quality a little worse	3.4%	4.5%

Table 10: Daylight quality and work quality in the EC and LeG buildings.

### Office Lighting Quality and Visual Comfort

There was no significant difference in responses between buildings with the EC and those with LeG (Table 11) and most respondents said that the office lighting quality was comfortable in the EC buildings (80.6%) and in the LeG buildings (63.6%).

Office lighting quality and visual comfort	EC (n=267)	LeG (n=44)
Very comfortable	44.6%	34.1%
Fairly comfortable	36.0%	29.5%
Neutral	12.0%	25.0%
Fairly uncomfortable	6.0%	9.1%
Very uncomfortable	1.5%	2.3%

Table 11: Office lighting quality and visual comfort in the EC and LeG buildings.

### Opinion of Window Glass in Current and Previous Offices

Only the workers in the EC buildings were asked “How do you compare the window glass in your current office with that in your previous office?” As shown in table 12, there was a strong preference for the current glass in the EC buildings (70.7%).

Window glass preference	EC (n=242)
Prefer current glass	70.7%
No preference	14.5%
Prefer other glass	9.5%
Not worked elsewhere	5.4%

Table 12: Opinions on the window glass in current and previous offices in the EC buildings.

### EC Buildings Opinions

Workers in the EC buildings were asked “How do you feel about working in your office and in this office building?”, and many respondents said that they felt excited to be working in their EC buildings, that they felt proud of their building and that the EC helps to create a more productive and healthier workplace.

I feel excited to work in this building	65.6%
I feel proud to work in this building	54.6%
The glass in this building helps to create a more productive work environment	39.6%
The glass in this building helps to create a healthier work environment	38.8%
I would recommend working in this building to others	33.9%
I feel relaxed when I work in this building	10.1%

Table 13: Respondents' opinions about working in the EC buildings (n=227).

### Discussion

Many studies of the effects of lighting employ short-term laboratory experimental exposures. However, unless the anticipated lighting variable has an acute effect such short-term studies may fail to reveal the effects of longer term exposures. An analogous situation might be determining the efficacy of an antibiotic, where an effect seldom is seen after a single dose but rather requires repeated doses over time for maximum efficacy. Consequently, field experimental and comparative lighting studies in real-world settings often can reveal more subtle effects that may be potentially masked in a short-term laboratory exposure.

The present comparative field survey of workers in office buildings with EC or with LeG revealed several significant results. In the EC buildings, more workers sat closer to the windows than in the LeG offices, and consequently, more workers reported sun views, better daylight quality, and better overall lighting quality. EC is designed to allow an outside view but to minimize any glare issues, and the survey results showed that there was no difference in reports of glare between the EC buildings, where many more workers sat close to the windows, and the LeG offices where they sat further from the windows and fewer had a sun view. This suggests that the EC was working as designed to minimize glare while blocking the heat without compromising an outdoor view.

In future research, it would be useful to collect data on the performance of the EC windows and data on the collect data on the use of any blinds in the LeG buildings to further test this possible explanation of the survey results

There was a significantly lower prevalence of eyestrain and headache complaints, both symptoms of CVS, along with higher levels of satisfaction with lighting quality and positive opinions of how the windows improved lighting quality in the EC buildings. As noted by Blehm et al. [13] CVS, which in 2005 was a \$2 billion problem, the causes can be multifactorial, but they definitely include lighting, glare, and screen display design characteristics. The present study only collected survey responses and lighting and glare issues, and future research should try to gather objective measures of glare and also examine screen design characteristics for a more complete picture of how EC beneficial reduces CVS risks.

As noted in the introduction, there is a growing literature on the beneficial effects of blue enriched light exposure on alertness and cognition [17,19-22]. Previous research has found that blue light improves alertness and the present study also found that workers in the EC buildings reported significantly less drowsiness and greater alertness, and this may be because of the blue light that is transmitted through the EC even in its darkest tint state. However, several previous studies have evaluated enhanced blue light for workers on shifts, whereas the present research only addressed daytime working. In section 54 (Circadian Lighting Design) of the WELL V2 building performance system it is emphasized that “the biological effects of light on humans can be measured in Equivalent Melanopic Lux (EML)” [17,25,26]. Future research should objectively measure the blue light component to see the effects of EC on the EML and whether this could be the reason for the alertness finding.

Similar opinions were recorded from workers in the EC and LeG buildings for reports of daylight glare, effects of windows on lighting quality and productivity, mood, health and well-being, energy, and improvements in work quality. This may either indicate an equivalence between the buildings or more likely it indicates a limitation of the research design because workers in the EC mostly had prior experience of buildings with LeG and consequently they were able to provide comparative judgments of their EC experience compared with their prior experiences, whereas workers in the LeG had no experience of the EC environment.

Consequently, they may have interpreted some of the questions as being more general and they may have

responded more generally to questions about say “the importance of daylight”. However, workers in the EC buildings did voice positive opinions about the quality of the visual environment with EC.

There are other limitations with the current research. Worker samples were self-selected and sample sizes were uneven. From the survey it wasn't possible to know the precise content of their work in terms of its visual demands which could be affected by windows and daylight. Objective measures of the visual environment were not available (e.g. illuminance levels, variations in the transmittance of the EC). Objective measures of work performance were not available. Consequently, although the present study shows several favorable results for the EC, these should not be interpreted as definitive findings until further research has been undertaken.

Future studies could usefully compare the potential benefits of EC in both pre-installation and post-installation surveys of workers in the same organization. Studies could also comparatively evaluate the performance of workers in EC and LeG buildings over longer timeframes and with more detailed information on where respondents work in a building and what their lighting exposures are over time.

Previous research has shown the benefits of EC for reducing the energy requirements for office buildings [15]. Limitations apart, the present study shows that EC can improve the visual environment to improve the satisfaction of workers, reduce the prevalence of CVS symptoms, and foster positive feelings about their visual environment at work.

### Acknowledgement

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