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Multi-Season Assessment of Occupant Responses to Manual Shading and Dynamic Glass in a Workplace Environment

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Abstract: The quality and controllability of the building façade can significantly contribute to building indoor environmental quality (IEQ) as well as the building's energy efficiency. Advanced technologies that support a façade's dynamic response to climatic changes, such as electrochromic (dynamic) glazing, have emerged as smart systems for IEQ and environmental sustainability. This research summarizes a four-season study of office workers moving from a floor with conventional blinds to work environments equipped with smart dynamic glazing which changes tint in response to weather condition to control daylighting levels. Multiple occupant environmental satisfaction surveys were conducted over one year to investigate differences in environmental and psychological responses to office settings with manual, and often static, facades as compared to offices with dynamic glazing. This research confirms that dynamic glazing significantly affected occupants' environmental satisfaction—enhancing individuals' environmental perceptions and psychological health—as compared to manual blinds. It reveals that the occupants in work environments with dynamic glazing reported 21.7% higher productivity gains, 24.8% increased ability to relax, 12.7% improved concentration, 25.3% better moods and 29.4% greater alertness than when they were in offices in the same building with manual shading devices. Also, the dynamic feature of the smart glazing showed a significant contribution to perceived work productivity while enhancing positive emotional responses by an average of 26%.

Keywords: occupant well-being; dynamic façade; smart windows; electrochromic windows; work productivity; indoor environmental quality

1. Introduction

In today's buildings, the importance of indoor environmental quality (IEQ) has been increasing, especially the factors of thermal and visual quality, due to its significant impacts on occupants' productivity, health, and quality of life [1–10]. This indoor environmental significance has motivated numerous design and technology advancements, especially as applied to modern building environmental controls. Specifically, technological advances have been made to accommodate dynamic features in the building façade systems [11–14]. Among those advances, electrochromic glazing, called the "dynamic window", has emerged in the high-performance building domain. Since this dynamic façade can be controlled as a function of solar radiation and daylight availability, it contributes to building energy performance, indoor thermal and lighting quality, user satisfaction, and environmental sustainability. Most significantly, dynamic glazing is known to contribute to reduced glare, thermal discomfort and reduced cooling loads. The visual transmittance of dynamic glazing can be increased or decreased based on pre-defined control algorithms, and it can control the illuminance of natural light admitted through glazing in an optimal way to enhance the visual quality and allow for continuous window views without compromising the thermal-quality condition. These technical merits have been especially important for office and healthcare facilities where the occupants' environmental health and work productivity are important.

Recent research has investigated the efficacy of dynamic glass, focusing predominantly on energy performance. Tavares et al. investigated the energy conservation potential of adopting electrochromic windows in a Mediterranean climate [15]. The research confirmed that electrochromic glazing saved 15–20% energy in a cooling dominant climate depending on orientation, and the impact was most significant for the west façade. DeForest et al. simulated energy consumption of three building types in 16 U.S. climate zones, identifying that electrochromic windows outperformed other glazing choices in x of the 48 set of locations and building types [16]. Picco et al. used both experimental tests and computation simulations to evaluate the impact of electrochromic glazing on energy efficiency [17]. This study tested four different strategies and revealed the energy consumption differences ranging from 4% to 10%. This study also identified that a simpler control strategy, such as rule-based control (RBC), can achieve a similar energy performance, as compared to a complex control strategy, such as model-predictive control (MPC).

In addition to the energy conservation benefits of dynamic glazing, the impacts of dynamic glazing on IEQ has also been investigated. Li et al. conducted a comparative analysis of daylight control between two office rooms, one with electrochromic windows and the other with low-e glazing, using occupant surveys. This study revealed that occupants in offices with electrochromic windows reported greater satisfaction with glare control by reducing indoor brightness [18]. Ajaji and Andrea identified a significant reduction in overheating and prevention of over-illumination in the office environment with electrochromic windows [19]. Lee et al. monitored and evaluated the energy performance and IEQ control of the electrochromic windows in a conference room [14]. A significant reduction of the use of manual (overriding) control on the blinds by the occupants was also reported. Through simulation, this study found 91% of lighting energy savings were accomplished as compared to the original glazing with manual blinds.

Most of the recent studies investigating the impact of dynamic glazing on energy efficiency and indoor environmental quality have focused on energy performance only. Therefore, the objective of this research was to investigate the impact of dynamic glazing on occupant environmental satisfaction and psychological perception by comparing the same group of office workers in two different office environments: one equipped with manual horizontal blinds and the other with dynamic glazing. The research used a range of a pre- and post-survey tools to assess occupancy satisfaction, mood, perceived health and performance and their environmental experiences.

2. Methodologies

This study was undertaken in an office building in Toronto, Canada, surveying occupants before and after a relocation from one office floor to another in the same building. The before study was completed with 17 office occupants on the 12th floor, occupying both closed and open workstations on a floor with conventional glazing and manual venetian blinds to control glare and overheating. These occupants were relocated to the 17th floor for business reasons, and the glazing and blind assembly was replaced with electrochromic glazing as a testbed for future renovations. Figure 1 shows the office building with blinds in various stages of openness, with the 17th-floor glazing in low transmission status.

Figure 1. Facade view of the office building selected for this study.

Seventeen office occupants answered the surveys that were adopted in this study. All of them were employees of the selected office, and the survey was conducted routinely as part of their commitments during their business. The initial survey was conducted before the move, and the collected data was adopted as a baseline for the research, as pre-study data. After the move, the survey was regularly conducted per season, in May for spring, August for summer, and December for winter. Table 1 summarizes the climate conditions of each survey date.

Table 1. Outdoor weather conditions for the data-collection dates.

Environmental Parameter	April	May	August	December
Glazing condition	**Blinds**	**Dynamic**	**Dynamic**	**Dynamic**
High temperature (°C/°F)	17.8/64	20.6/69	31.1/88	2.2/36
Low temperature (°C/°F)	3.3/38	10/50	21.7/71	−5/23
Day average temperature (°C/°F)	10.6/51	15.6/60	26.7/80	−1.1/30
Day average humidity (%)	48%	45%	67%	68%

Three surveys were deployed across the three seasons: the Oxford Questionnaire [20], the Kansei Engineering Survey [21–23], and the Cost-effective Open-Plan Environments (COPE) survey [24], engaging the cohort of 17 office workers in the springtime move from 12th floor offices with Low-E glazing and manual venetian blinds to 17th floor offices with dynamic glazing and no blinds (Figure 2). The Oxford questionnaires include multiple questions asking about an individual occupant's thermal, lighting, air, and acoustic satisfaction, while the Kansei Engineering questionnaires mainly assess psychological perceptions that include negative and positive emotional responses to the user's ambient environmental conditions. The third used was the COPE survey, developed by the National Research Council in Canada to examine the effect of office design choices on the workplace environment in open-plan offices, and on occupant satisfaction [25]. This survey has been modified by Carnegie Mellon's Center for Building Performance in collaboration with the U.S. General Services Administration to ensure a better understanding of indoor environmental quality on workplace satisfaction and performance. This survey questionnaire is a short 'right now' assessment of environmental and job satisfaction, based on a seven-point scale from 1: very dissatisfied, 2: dissatisfied, 3: slightly dissatisfied, 4: neutral, 5: slightly satisfied, 6: satisfied, and 7: very satisfied.

Figure 2. Overview of the glazing on the selected floors in the selected building.

Throughout the study, the building HVAC and lighting system and management remained constant, as did workers' job functions and the organization's management team. Both the floors adopted overhead air-distribution systems with a seasonal change-over control based on the same schedule. They also adopted the same lighting systems that dominantly have T-12 lamps with no flush lens. Climate conditions were tracked to evaluate potential seasonal effects (Table 1). The move did result in fewer enclosed offices and more open plan workstations, with some reductions in average workstation size, to be further addressed relative to overall satisfaction, perception and emotional response. This study adopted the Minitab software for statistical analyses, with two-sample T-tests, analysis of variance, and paired T-tests for the pre- and post-analysis [26]. The statistical analysis provides a multi-season evaluation of the impact of dynamic glazing on employee environmental satisfaction, perceived health and task performance, and emotional responses, across the four individual datasets, and the average of the three with dynamic glazing, labeled as:

- 12th floor with manual blinds—Spring dataset (collected on April): Blinds-Spring
- 17th floor with dynamic glazing—Spring dataset (collected May): Dynamic-Spring
- 17th floor with dynamic glazing—Summer dataset (collected August): Dynamic-Summer
- 17th floor with dynamic glazing—Winter dataset (collected December): Dynamic-Winter
- 17th floor with dynamic glazing—Average of Spring, Summer, and Winter datasets: Dynamic-Average

As illustrated in Figure 3, the 17 office workers engaged in the study were distributed as follows: 12 female, 5 male before and after;16 closed offices before and 5 after the move, 12 perimeter offices before and 9 after the move; from offices with manual blinds to offices with dynamic glazing—all in the same building. The user response study was repeated in spring, summer, and winter to explore whether user responses were consistent across time and weather conditions. All 17 workers were constant across the first three data sets (Spring Manual Blind, Spring Dynamic Glazing and Summer Dynamic Glazing) with a loss of two users in the final Winter surveys. An additional control floor with offices with manual blinds in the same building was added for the winter study to adopt an additional seasonal control set, although the subjects were not previously surveyed.

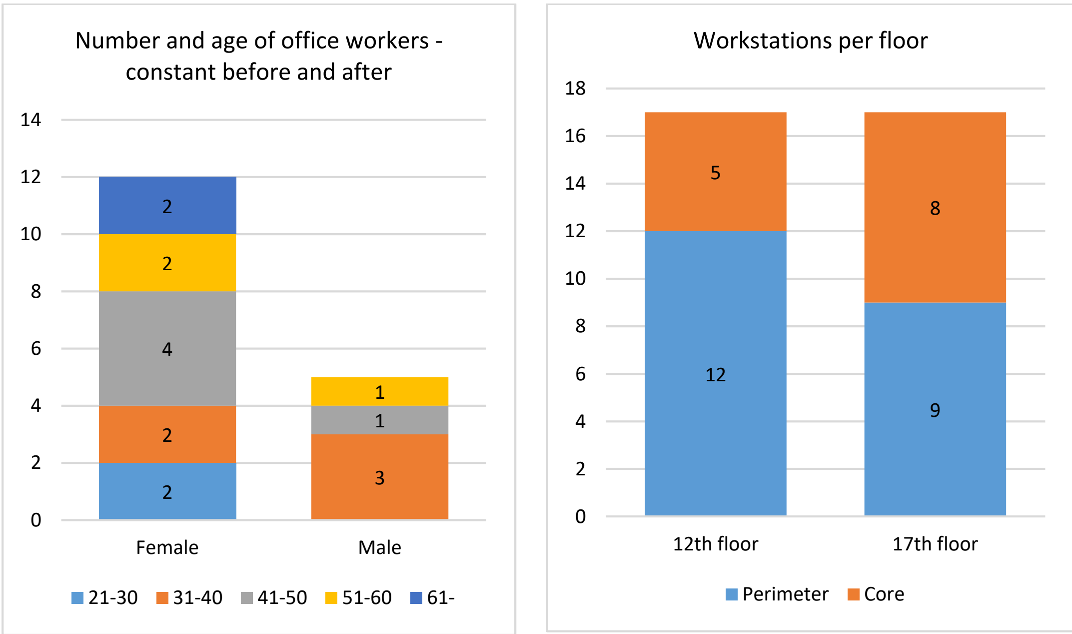


Figure 3. Demographic and architectural information of 12th floor (blinds) and 17th floor (dynamic glazing).

Given the demographic variations, statistical analyses were performed with strategic groupings of data sets by glazing type, workstation location, and season; 66 datasets of illuminance measurement and satisfaction surveys were collected in the manual blinds and dynamic glazing offices during the study period. Correlational analysis, 2-sample *t*-test, and analysis of variance (ANOVA) comprised the data investigations [26].

- Correlation analysis: this was used to estimate the correlation between two different groups by generating a correlation index (i.e., −1 to 1) to quantify the direction and strength of the linear or non-linear association. Since the sampled data collected in this study mostly follows the linear correlation between datasets analyzed, the Pearson correlation method was adopted.
- Two-sample *t*-test: was used to analyze sampled data from two groups while comparing the distributions as a function of the t-value. This test is frequently adopted for evaluating the means of two variables or distinct groups while confirming whether the means between two populations differs.
- ANOVA: this is a collection of statistical models used to confirm the variation among groups, which is frequently adopted to analyze the differences among multiple groups, i.e., more than two groups, in a sampled data. This analysis is effective in this study to compare the environmental or emotional condition data collected from multi-age groups. The project adopted the following statistically significant thresholds:
    - 95%—Statistically significant (highlighted in red with “*”)
    - 90%—Marginally statistically significant (highlighted in red without “*”)

The following sections summarize the multi-season responses to the move from offices with manual shading to offices with dynamic glazing, in three distinct outcome areas: Environmental Satisfaction, Physiological Responses related to health and productivity, and Emotional Responses related to the perceived changes in light, glare, view and thermal conditions.

3. Results and Discussion

3.1. Environmental Satisfaction in Offices with Manual Blinds versus Dynamic Glazing across Three Seasons

On average, the participants reported statistically significant increases in environmental satisfaction (p-values < 0.001) across all three seasons with dynamic glass as compared to those same seasons with manual blinds (i.e., Blinds-Spring). As summarized in Table 2, there was a 40.6% increased satisfaction with overall "lighting and window view to the outside" in offices with dynamic glazing. In addition, there was a 38% increased satisfaction with the quality of daylight and a 33.8% increased satisfaction with the overall quality of light in the pre- and post- comparisons.

3.2. Perceived Individual Performance Impact from Lighting, Daylighting and View

One hypothesis of the potential benefits of dynamic glazing over manual blinds in improving user satisfaction, perceived performance and mood is the possibility of greater daylighting on work surfaces when daylight levels are low and reduced glare when daylight levels are high. It was anticipated that daylight contributions on the floor with dynamic glazing would increase light levels overall, however, spot measurements did not reveal statistical differences. While actual illuminance levels on the worksurface were not significantly different between offices with manual blinds and dynamic glazing (as illustrated in Figure 4), the occupants perceived enhanced light and daylight conditions in the offices with dynamic glazing, which contributed to parallel gains in physiological perceptions across all three seasons, as shown in Figure 4. The lack of any seasonal variation in ANOVA responses for workers in offices with dynamic glazing across spring, summer, and winter datasets (Table 3) confirmed that the workers' relevant perceptions of productivity were consistently enhanced by dynamic glazing in all seasons (on a 10 point scale from −5 really hinders to +5 really helps). The occupants in work environments with dynamic glazing reported 21.7% higher productivity gains, 24.8% increased the ability to relax, 12.7% improved concentration, 25.3% better moods and 29.4% greater alertness than when they were in offices in the same building with manual shading devices.

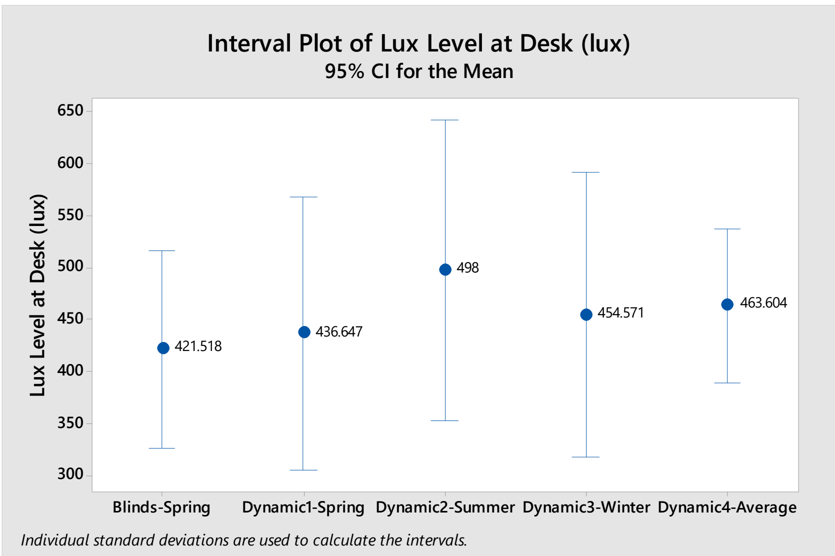
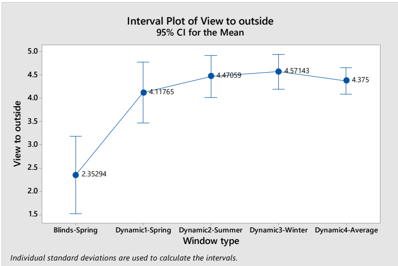
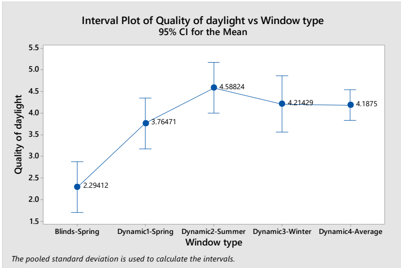
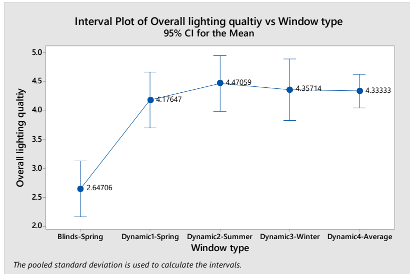
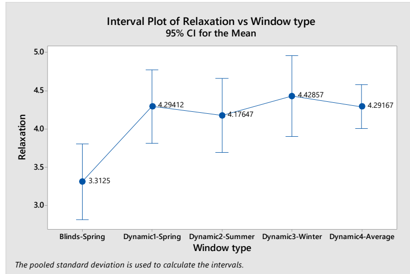
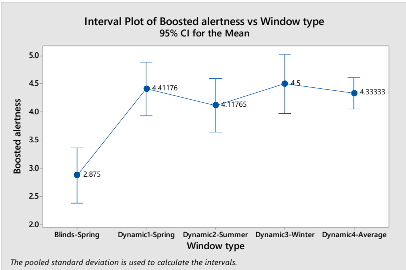
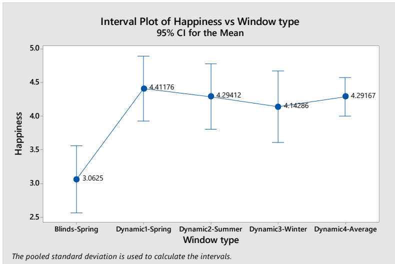
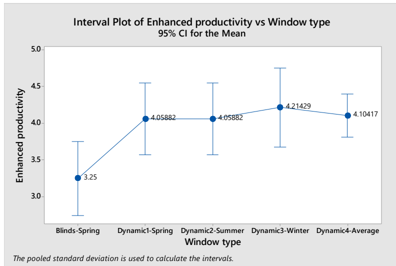
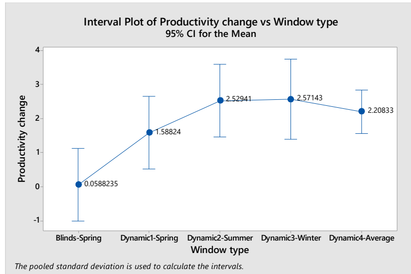
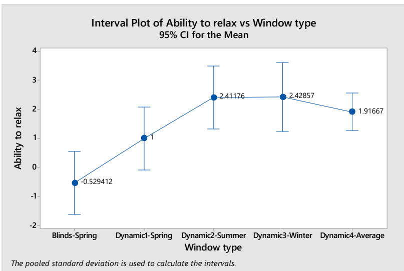
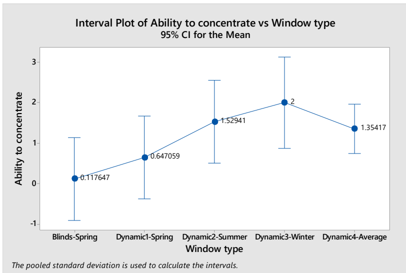
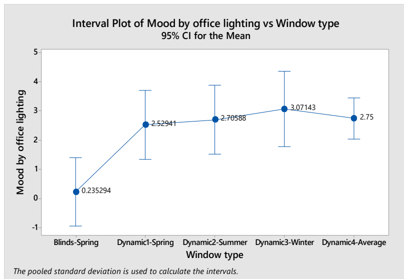
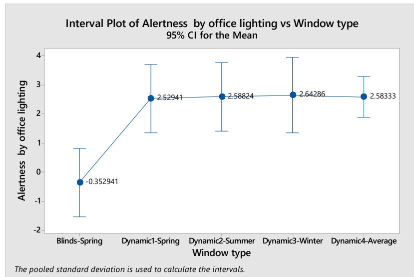


Figure 4. Distribution of illuminances for individual office environments across seasons shows no statistically significant variation (p-value = 0.916 in ANOVA).

Table 2. Manual blinds (12) Spring vs. Dynamic Glazing (17) Spring, Summer, and Winter environmental satisfaction. (* ANOVA: Analysis of Variance)

#	Item	Blinds-Spring N = 17	Dynamic				ANOVA *p*-Value (Blinds-Dynamics)	Dynamic Average	Difference (Dynamic-Blinds) (Score)	% Change at 5 pt Scale (Dynamic-Blinds) (%)
			Spring N = 17	Summer N = 17	Winter N = 14	ANOVA* *p*-Value (Dynamic)				
	Multiple choice index; 5 Excellent, 4 Good, 3 Fair, 2 Poor, 1 Very poor *(higher value is better) (5 point-scale)*									
1	Lighting and window view to outside	**2.35**	4.12	4.47	4.57	0.40	$p < 0.001$*	**4.39**	**2.03**	**40.6%**
2	Quality of light	2.29	3.77	4.59	4.21	0.10	$p < 0.001$*	**4.19**	**1.90**	**38.0%**
3	Overall lighting	2.65	4.18	4.47	4.36	0.67	$p < 0.001$*	**4.33**	**1.69**	**33.8%**
	Multiple choice index; 5 Strongly agree, 4 Agree, 3 Neutral, 2 Disagree, 1 Strongly disagree *(higher value is better) (5 point-scale)*									
4	Daylight and my view helps me to relax	3.31	4.29	4.18	4.43	0.72	0.027*	**4.30**	**0.99**	**19.8%**
5	I like my view out of my windows	3.00	4.59	4.18	4.50	0.44	0.001*	**4.42**	**1.42**	**28.4%**
6	Daylight and my view boosts my alertness	2.88	4.41	4.12	4.50	0.41	$p < 0.001$*	**4.34**	**1.47**	**29.4%**
7	Daylight and my view helps me feel happier	3.06	4.41	4.29	4.14	0.72	0.003*	**4.28**	**1.22**	**24.4%**
8	Daylight and my view helps my productivity	3.25	4.06	4.06	4.21	0.88	0.055	**4.11**	**0.86**	**17.2%**
9	I don't get good daylight and a clear window *(lower value is better)*	3.18	1.77	1.77	1.29	0.49	0.001*	**1.61**	**−1.57**	**−31.4%**
	Multiple choice index; 10 point scale 5 (Really helps) 0 (No effect) −5 (Really hinders) *(higher is better) (10 point-scale)*									
10	Productivity change by office lighting (Daylight and Electric)	0.06	1.59	2.53	2.57	0.35	0.007*	**2.23**	**2.17**	**21.7%***
11	Ability to relax by office lighting (Daylight and Electric)	−0.53	1.00	2.41	2.43	0.10	0.001*	**1.95**	**2.48**	**24.8%**
12	Ability to concentrate by office lighting (Daylight and Electric)	0.12	0.65	1.53	2.00	0.19	0.073	**1.39**	**1.27**	**12.7%**
13	Mood by office lighting (Daylight and Electric)	0.24	2.53	2.71	3.07	0.81	0.009*	**2.77**	**2.53**	**25.3%**
14	Alertness by office lighting (Daylight and Electric)	−0.35	2.53	2.59	2.64	0.99	0.002*	**2.59**	**2.94**	**29.4%**

Table 3. Indoor environmental quality (IEQ) satisfaction changes using the Oxford Questionnaire by window condition and season. "*": Statistical significance.

View to Outside $p < 0.001$*	Quality of Daylight $p < 0.001$*	Overall Lighting Quality $p < 0.001$*	Relaxation $p = 0.027$*
			
Boosted Alertness $p < 0.001$*	**Happiness $p = 0.003$**	**Enhanced Productivity $p = 0.055$**	**Productivity Change by Office Lighting $p = 0.007$***
			
Ability to Relax w/ Office Lighting $p = 0.001$*	**Ability to Concentrate w/ Office Lighting $p = 0.073$**	**Mood w/ Office Lighting $p = 0.009$ ***	**Alertness w/ Office Lighting $p = 0.002$***
			

3.3. Subjective Responses of Physiological Health Symptoms Related to Glare

Physiological responses significantly improved following the move from offices with manual blinds to those with dynamic glazing, across all three seasons, as illustrated in Figure 5. Incidence of reported eye fatigue by glare dropped from 12 occupants (71%) to 3 occupants (21%); reported annoyance by glare dropped from 10 occupants (59%) to 4 occupants (24%), reported visual discomfort at computer work dropped from 10 occupants (59%) to 4 occupants (24%), and reports of disruption in concentration dropped from 7 (41%) occupants to 2 (15%) occupants. Complaints of headaches due to glare dropped from 5 in 17 occupants (29%) in offices with manual blinds, to a low of 1 occupant (6%) in the summer months in offices with dynamic glazing and tuned control algorithms, with an average of 3 occupants (17%) across all seasons. Dynamic glazing also contributed to a significant reduction in thermal stress and, effectively, the elimination of drowsiness.

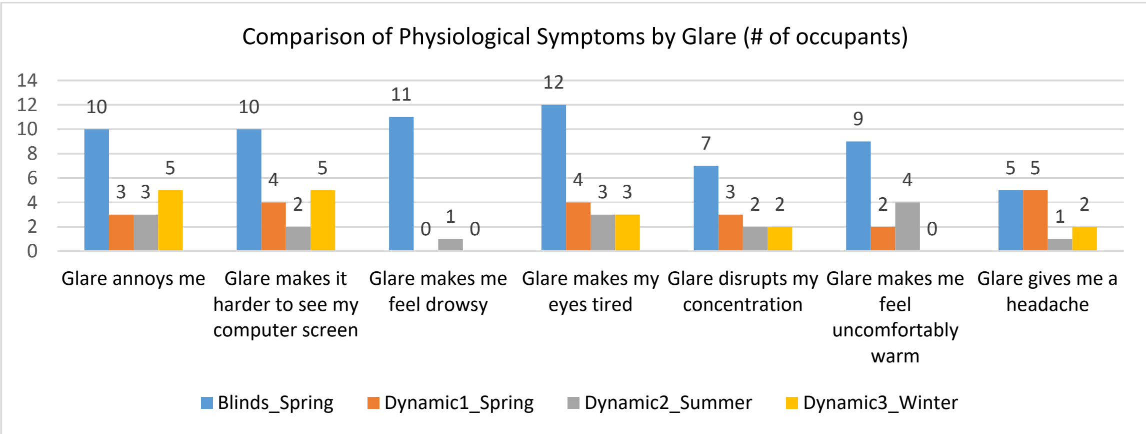


Figure 5. Physiological symptoms by glare (unit: number of occupants).

3.4. Positive and Negative Emotional Responses to Changes in Window Shading Solutions

The 'radar' charts in Figure 6 illustrate the sustained increase in 12 positive emotional responses in the offices with dynamic glazing during the spring, summer, and winter, as compared to responses in offices with manual blinds that were recorded before the move in the spring ($p < 0.002$, Table 4). After the Spring move, the same 17 occupants were re-engaged in the surveys, where the full range of positive emotional responses significantly increased, including responses to the impressions relating to: energized, excited, delighted, happy, calm, relaxed, serene, comfortable, pleased, and bright. Remarkably, this pattern held through Summer and Winter surveys. This is a testament to the effectiveness of dynamic glazing for ensuring access to views, managing overheating and glare in the Summer months, and managing the effects of lower light and shorter days in the Winter. Table 4 illustrates this consistent 26% average increase in positive emotional responses in the offices with dynamic glazing in the Spring, Summer, and Winter, as compared to responses from the same workers in offices with manual blinds in the Spring (given the 5-point scale in the survey).

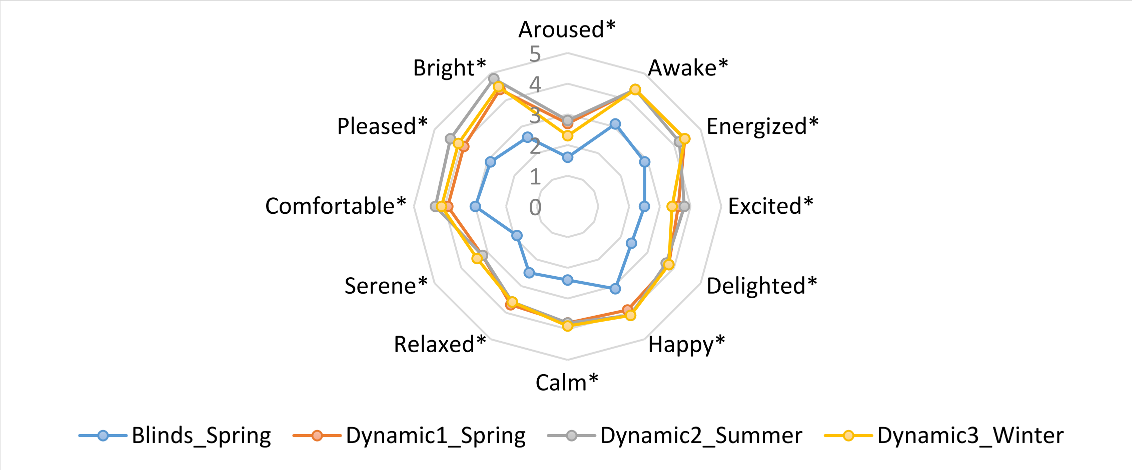


Figure 6. Radar chart of positive emotional responses comparing offices with manual blinds versus dynamic glazing (all comparisons are statistically significant with a *p*-value of < 0.05).

Table 4. Positive emotional responses and differences. "*": Statistical significance.

Emotional Response	Blinds_ Spring	Dynamic1_ Spring	Dynamic2_ Summer	Dynamic3_ Winter	Dynamic_ Average	Difference (Score)	Difference (%)	*p*-Value
Aroused	1.6	2.7	2.8	2.3	2.6	1.0	20%	0.002*
Awake	3.1	4.4	4.4	4.4	4.4	1.3	26%	$p < 0.001$*
Energized	2.9	4.4	4.2	4.4	4.3	1.5	30%	$p < 0.001$*
Excited	2.5	3.6	3.8	3.4	3.6	1.1	22%	0.001*
Delighted	2.4	3.8	3.7	3.8	3.8	1.4	28%	$p < 0.001$*
Happy	3.1	3.9	4.1	4.1	4.0	0.9	18%	0.008*
Calm	2.4	3.8	3.8	3.9	3.8	1.5	30%	$p < 0.001$*
Relaxed	2.5	3.7	3.6	3.6	3.7	1.1	22%	$p < 0.001$*
Serene	1.9	3.2	3.2	3.4	3.2	1.3	26%	$p < 0.001$*
Comfortable	3.0	3.9	4.3	4.1	4.1	1.1	22%	$p < 0.001$*
Pleased	2.9	3.9	4.4	4.1	4.1	1.2	24%	0.002*
Bright	2.6	4.4	4.8	4.5	4.6	1.9	38%	$p < 0.001$*
					Average	**1.3**	**26%**	

After the April move, the same 17 occupants were re-engaged in the surveys measuring negative impressions to the workspace with only 6 statistically significant differences. In a complementary set of questions relating to 12 negative emotional responses to work environments—including tense, upset, annoyed, distressed, frustrated, bothersome, miserable, gloomy, sad, boring, dark, and tired—this study demonstrated an average 22% decrease in 6 negative emotional responses in the offices with dynamic glazing over the three seasons as compared to responses from before the move in offices with manual blinds, recorded in the Spring ($p < 0.057$; Figure 7; Table 5). The other 6 negative emotional responses revealed an average of 6% drop in offices with dynamic glazing, but these were not statistically significant. Among the significant responses, boring, dark, and tired, (which may be directly or indirectly related to work productivity) posted relatively larger reductions (26% to 30%) as compared to other negative emotional responses.

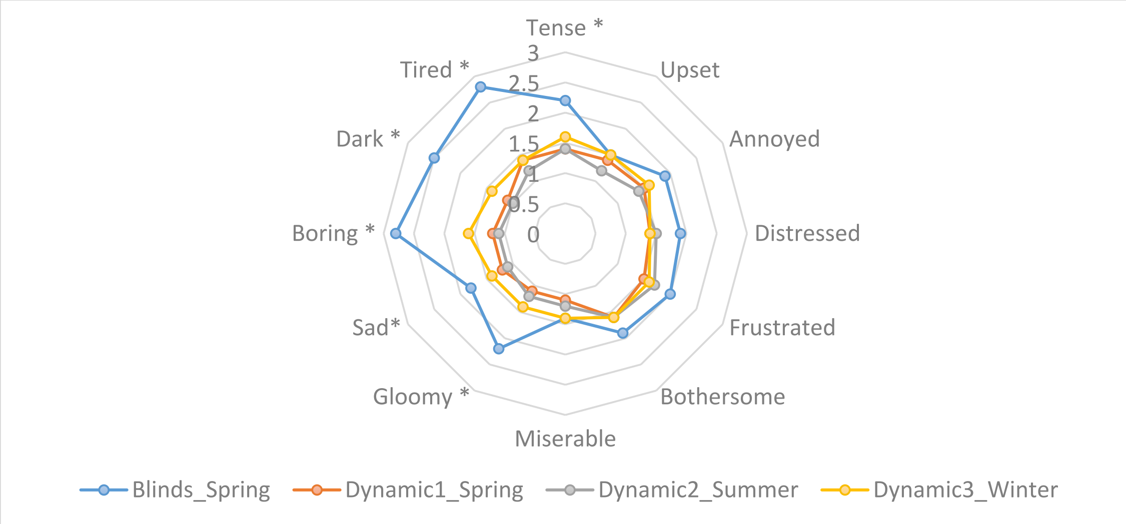


Figure 7. Radar chart of negative emotional response comparing offices with manual blinds versus dynamic glazing (stars denote statistical significance with *p*-value of < 0.05).

Table 5. Negative emotional responses and differences. "*": Statistical significance.

Emotional Response	Blinds_ Spring	Dynamic1_ Spring	Dynamic2_ Summer	Dynamic3_ Winter	Dynamic_ Average	Difference (Score)	Difference (%)	*p*-Value
Tense	2.2	1.4	1.4	1.6	1.5	−0.8	−16%	0.030*
Upset	1.5	1.4	1.2	1.5	1.4	−0.1	−2%	0.647
Annoyed	1.9	1.5	1.4	1.6	1.5	−0.4	−8%	0.261
Distressed	1.9	1.4	1.5	1.4	1.4	−0.5	−10%	0.183
Frustrated	2.0	1.5	1.7	1.6	1.6	−0.4	−8%	0.240
Bothersome	1.9	1.6	1.6	1.6	1.6	−0.3	−6%	0.336
Miserable	1.4	1.1	1.2	1.4	1.2	−0.2	−4%	0.443
Gloomy	2.2	1.1	1.2	1.4	1.2	−1.0	−20%	0.013*
Sad	1.8	1.2	1.1	1.4	1.2	−0.5	−10%	0.057
Boring	2.8	1.2	1.1	1.6	1.3	−1.5	−30%	0.001*
Dark	2.5	1.1	1.0	1.4	1.1	−1.3	−26%	0.004*
Tired	2.8	1.4	1.2	1.4	1.3	−1.5	−30%	$p < 0.001$*
					Average	**−0.7**	**−14%**	

3.5. The Impact of Workstation Perimeter and Core Locations on Satisfaction, Perceived Performance, and Mood

Across POE studies, it is frequently reported that occupants' environmental and emotional responses are significantly higher in perimeter offices as compared to core or interior offices. Considering the improved thermal and visual environmental perceptions in offices with dynamic glazing compared to manual blinds, it is important to investigate whether the impacts of dynamic glazing related to environmental perceptions are dependent or independent of perimeter and core locations. This is even more pressing since the move reduced the number of employees in perimeter offices from 12 of 17 in offices with manual blinds to 9 after the move to offices with dynamic glazing.

Based on the technical procedure outlined in Carnegie Mellon University (CMU)'s National Environmental Assessment Toolkit™ [24], workstations were defined as "perimeter" when they were within 15 feet of the window with seated views. "Core" workstations were thus defined as being located more than 15 feet from the façade or without seated views.

Statistical analysis reveals that employees in perimeter workstations with dynamic glazing have 27% greater satisfaction with window views to the outside and 22% greater satisfaction with the quality of lighting (3-season average) than they did in perimeter workstations with manual blinds (spring season). Surprisingly, the statistical analysis also reveals that employees in core workstations near workstations with dynamic glazing have 78% higher satisfaction with window views to the outside and 78% increased satisfaction with the quality of light (3-season average) than they did in core workstations near offices with manual blinds (spring season). This may be due to the likelihood that larger areas of the window will be clear for significant periods of time (when glare and overheating are not an issue), in comparison to windows with manual blinds (that are often left closed or $\frac{3}{4}$ closed after periods when shading is needed) (see Table 6).

In addition to these questions about environmental satisfaction and perceived task performance, the 24 positive and negative emotional responses were also evaluated between perimeter and core locations. In perimeter offices, all positive emotional responses improved in the move from offices with manual blinds (spring) to offices with dynamic glazing (all seasons), and 40% of the negative emotional responses were better in offices with dynamic glazing. In core offices, these gains in emotional responses were less pronounced, with statistically significant results in only five cases among 24 sets (see Table 7). Therefore, it was concluded that increases in access to daylight and views in both perimeter and core offices with dynamic glazing may even compensate for the loss of perimeter desk locations.

3.6. Cost-Effective Open-Plan Environments (COPE) Surveys: Comparing Environmental and Job Satisfaction to a Larger Database of Buildings

As quantified in the previous sections, the three-season internal comparison of responses from 17 employees who moved from offices with manual blinds to offices with dynamic glazing demonstrated statistically significant improvements in environmental satisfaction, perceived health and performance, and positive and negative emotional responses. However, there was a concern that the increases in satisfaction and perception could have been attributed to seasonal changes (fall and winter responses in comparison to spring), or unknown organizational changes, rather than the environmental changes offered by dynamic glazing. As a result, an additional set of surveys was introduced during the Fall and Winter studies, and for comparison to a larger database of user satisfaction responses in office buildings, as well as an additional control floor with manual blinds.

For this purpose, the project adopted the COPE satisfaction questionnaires as illustrated in 2. Methodologies. This survey was issued on the floor retrofitted with dynamic glass in both Fall and Winter time frames, and on an additional control office space on the 12nd floor of the same building with the more traditional venetian blinds, to assess whether seasonal or organizational changes might explain the increases in satisfaction, as shown in the analysis (see Table 8).

The advantages of the work environments with dynamic glazing were statistically significant for all key questions except job satisfaction and internally consistent across the two seasons (Table 9). The lack of statistical significance for job satisfaction is actually reassuring since environmental conditions do not play the dominant role in job satisfaction. Figure 8 summarizes the consistently higher COPE survey scores in offices with dynamic glazing conditions in fall and winter as compared to responses in the additional office floor with manual blinds surveyed in spring (adopted as the COPE baseline).

Table 6. Comparison of IEQ satisfactions in workstation locations between perimeter vs. core zones. "*": Statistical significance.

IEQ Parameter		Perimeter Zones				Core Zones			
#	**Item**	**Blinds_Spring (n = 12)**	**Dynamic_Average (n = 9)**	***p*-Value**	**Difference**	**Blinds Spring (n = 5)**	**Dynamic Average (n = 8)**	***p*-Value**	**Difference**
Multiple choice index; 5 Excellent, 4 Good, 3 Fair, 2 Poor, 1 Very poor *(higher value is better) (5 point-scale)*									
1	Lighting and window view to outside	3.25	4.593	$p < 0.001$*	27%	0.2	4.1	$p < 0.001$*	78%
2	Quality of light	3.17	4.26	0.019*	22%	0.2	4.1	$p < 0.001$*	78%
3	Overall lighting	3.25	4.37	$p < 0.001$*	22%	1.2	4.29	$p < 0.001$*	62%
Multiple choice index; 5 Strongly agree, 4 Agree, 3 Neutral, 2 Disagree, 1 Strongly disagree *(higher value is better) (5 point-scale)*									
4	Daylight and my view helps me to relax	4	4.11	0.782	2%	1.250	4.52	0.04	65%
5	I like my view out of my windows	3.67	4.44	0.08	15%	1	4.38	$p < 0.001$*	68%
6	Daylight and my view boosts my alertness	3.5	4.07	0.211	11%	1	4.667	$p < 0.001$*	73%
7	Daylight and my view helps me feel happier	3.75	3.96	0.538	4%	1	4.71	$p < 0.001$*	74%
8	Daylight and my view helps my productivity	3.75	3.85	0.771	2%	1.75	4.43	0.013*	54%
9	Window blinds interfere with good daylight	4.333	4.59	0.306	5%	3.75	4.62	0.030*	17%
10	I don't get good daylight and a clear window *(lower is the better)*	2.5	1.48	0.037*	−20%	4.8	1.81	$p < 0.001$*	
Multiple choice index; 10 point scale 5 (Really helps) 0 (No effect) -5 (Really hinders) *(higher is better) (10 point-scale)*									
11	Productivity change by office lighting (Daylight and Electric)	1.17	1.93	0.217	8%	−2.6	2.57	0.008*	52%
12	Ability to relax by office lighting (Daylight and Electric)	0.25	1.85	0.063	16%	−2.4	2	0.016*	44%
13	Ability to concentrate by office lighting (Daylight and Electric)	1.08	1.04	0.942	0%	−2.2	1.76	0.011*	40%
14	Mood by office lighting (Daylight and Electric)	1.67	2.7	0.152	10%	−3.2	2.81	0.004*	60%
15	Alertness by office lighting (Daylight and Electric)	1.08	2.3	0.168	12%	−3.8	2.95	0.001*	68%

Table 7. Comparison of emotional responses in workstation locations between perimeter vs. core zones. "*": Statistical significance.

Emotional Response		**Perimeter Zones**			**Core Zones**		
#	**Item**	**Blinds-Spring**	**Dynamic_Average**	***p*-Value**	**Blinds-Spring**	**Dynamic_Average**	***p*-Value**
	Survey below: higher is better.						
1	Aroused	1.417	2.519	0.002*	2	2.75	0.271
2	Awake	3.083	4.444	$p < 0.001$*	3.2	4.286	0.152
3	Energized	2.917	4.37	$p < 0.001$*	2.8	4.286	0.121
4	Excited	2.75	3.63	0.015*	1.8	3.57	0.004*
5	Delighted	2.33	3.81	0.001*	2.4	3.67	0.069
6	Happy	3	4.04	0.003*	3.4	4	0.334
	Survey below: lower is better.						
7	Tense	2.08	1.481	0.113	2.6	1.619	0.141
8	Upset	1.25	1.185	0.717	2	1.571	0.422
9	Annoyed	1.583	1.259	0.342	2.6	1.81	0.221
10	Distressed	1.67	1.222	0.2	2.4	1.67	0.304
11	Frustrated	1.833	1.37	0.178	2.4	1.9	0.474
12	Bothersome	1.75	1.333	0.206	2.4	2	0.419
13	Miserable	1.083	1.148	0.652	2.2	1.333	0.225
14	Gloomy	1.92	1.074	0.042*	2.8	1.333	0.145
15	Sad	1.5	1.074	0.06	2.4	1.43	0.19
16	Boring	2.5	1.222	0.007*	3.6	1.333	0.041*
17	Dark	2.08	1	0.035*	3.4	1.286	0.051
18	Tired	2.67	1.259	0.002*	3.2	1.381	0.055
	Survey below: higher is better.						
19	Calm	2.417	3.889	$p < 0.001$*	2.2	3.76	0.010*
20	Relaxed	2.583	3.815	$p < 0.001$*	2.4	3.48	0.008*
21	Serene	1.833	3.444	$p < 0.001$*	2.2	2.95	0.136
22	Comfortable	2.917	4.185	$p < 0.001$*	3.2	4	0.107
23	Pleased	3	4.192	0.005*	2.8	4.05	0.104
24	Bright	3	4.538	0.007*	1.8	4.667	0.005*

Table 8. Winter Comparison of lighting, thermal, overall IEQ, productivity, and job satisfaction on Cost-effective Open-Plan Environments (COPE) questionnaires from workers in offices with dynamic glazing and a comparison floor with manual blinds. "*": Statistical significance.

#	Type	Blinds	Dynamic	Dynamic	ANOVA
	1: Very Dissatisfied, 2: Dissatisfied, 3: Slightly Dissatisfied, 4: Neutral, 5: Slightly Satisfied, 6: Satisfied, 7: Very Satisfied.	**Spring**	**Fall**	**Winter**	
		Avg.	**Avg.**	**Avg.**	***p*-Value**
1	Light on desk for paper tasks	4.5	6.3	5.8	0.001*
2	Thermal comfort	3.0	4.9	4.4	0.006*
3	How do you feel about Light for computer work	4.7	6.5	6.0	$p < 0.001$*
4	How do you feel about overall quality of lighting your work area	4.9	6.5	5.9	0.001*
5	How do you feel about the following? [I am satisfied with my job]	6.1	6.5	6.1	0.188
6	How do you feel about the following? [The environmental conditions in my work area support my personal productivity]	4.4	6.0	6.1	0.011*
7	How do you feel about the following? [I am satisfied with the indoor environment in my work area as a whole]	4.5	5.6	6.0	0.050*

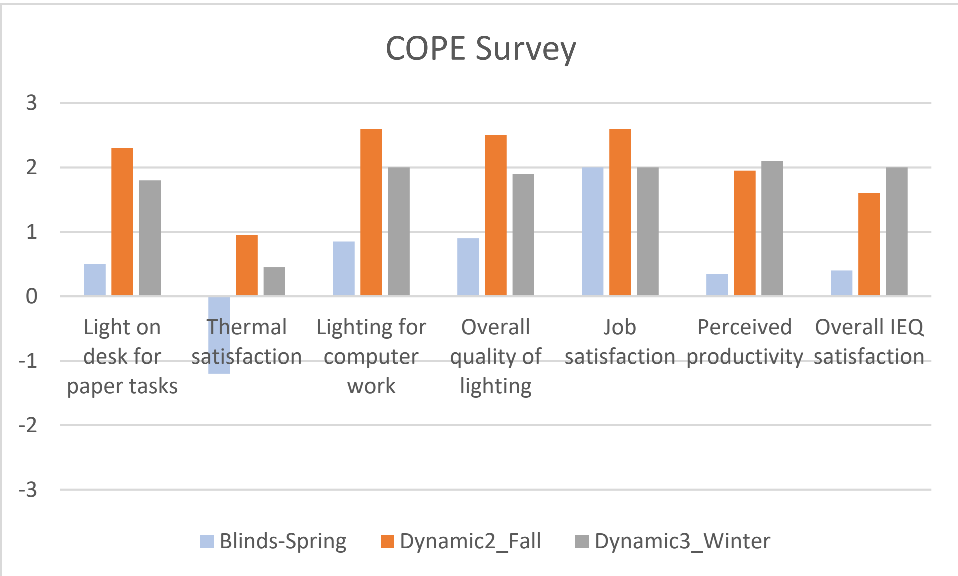
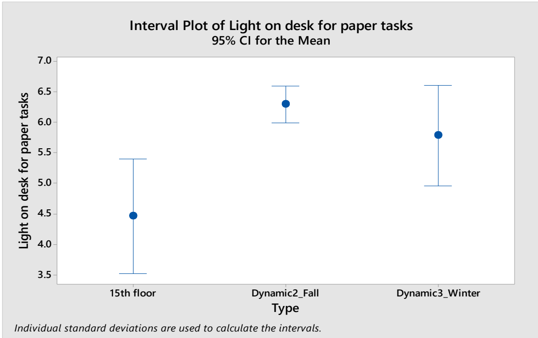


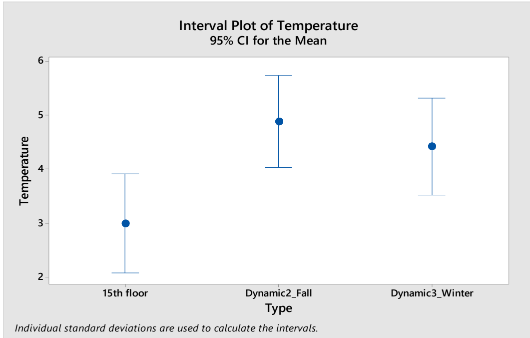
Figure 8. COPE survey: average satisfaction scores (y-axis) in offices with manual blinds in winter (light blue) as compared to offices with dynamic glazing in winter (grey) and dynamic glazing in fall (orange).

Table 9. Comparison of lighting, thermal, overall IEQ, productivity, and job satisfaction on COPE surveys. "*": Statistical significance.

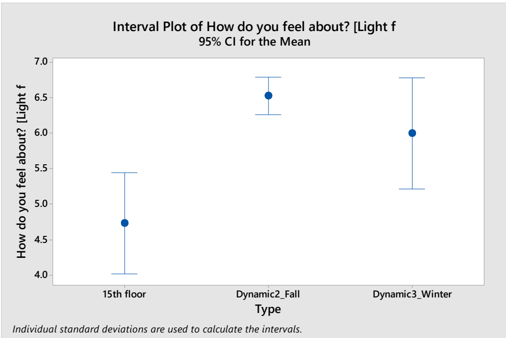
Light on desk for paper tasks ($p = 0.001$*)



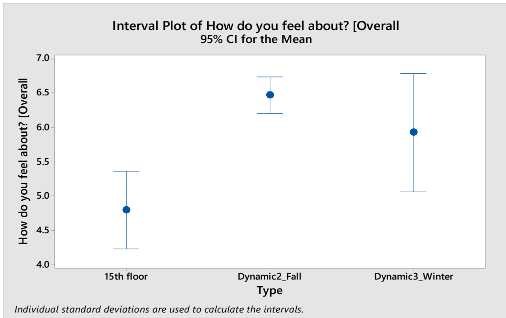
Thermal comfort ($p = 0.006$*)



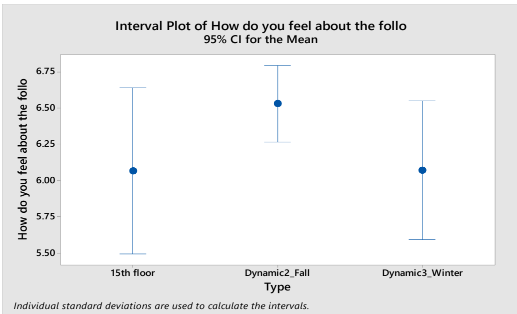
Light for computer work ($p < 0.001$*)



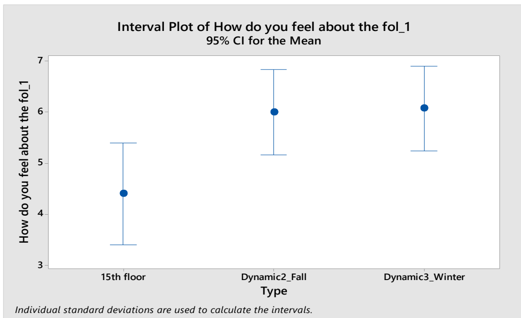
Overall quality of lighting ($p = 0.001$*)



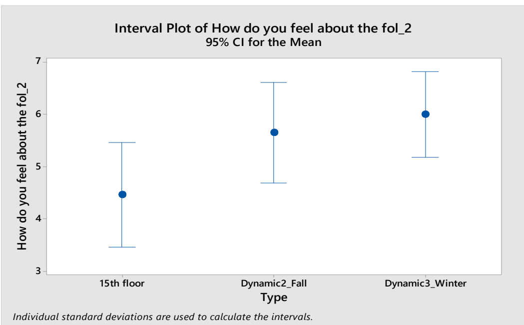
Job satisfaction ($p = 0.188$)



Personal productivity ($p = 0.011$*)



Overall IEQ satisfaction ($p = 0.05$*)



3.7. Comparison of Overall Environmental Satisfaction Using COPE Database

As illustrated in Table 10, COPE user satisfaction responses from the workers in offices with dynamic glazing, during summer and winter studies, yielded average overall IEQ satisfaction score in the top 7.5% of the COPE database of 2300 workstations across North America (red diamond). This is also measurably higher than responses in the offices with manual blinds (black diamond). The overall Thermal Satisfaction survey from the workers in offices with dynamic glazing shows a score in the top 9.5% in summer and 14.7% in winter of the COPE database. The performance of dynamic glazing seemed to generate moderately higher satisfaction in summer than in winter, possibly due to the increased shading capability of dynamic glazing. Also, the COPE survey yielded the overall Visual Satisfaction score in the top 12% in summer and 7.3% in winter in the office environment with dynamic glazing. The highest winter satisfaction is most likely due to the increased number of hours when clear views and daylight is made possible through dynamic glazing as compared to manual blinds that are often kept closed to cope with limited hours of low angle sun.

Table 10. Overall satisfaction in COPE (−3: very dissatisfied, −2: dissatisfied, −1: slightly dissatisfied, 0: neutral, 1: slightly satisfied, 2: satisfied, 3: very satisfied).

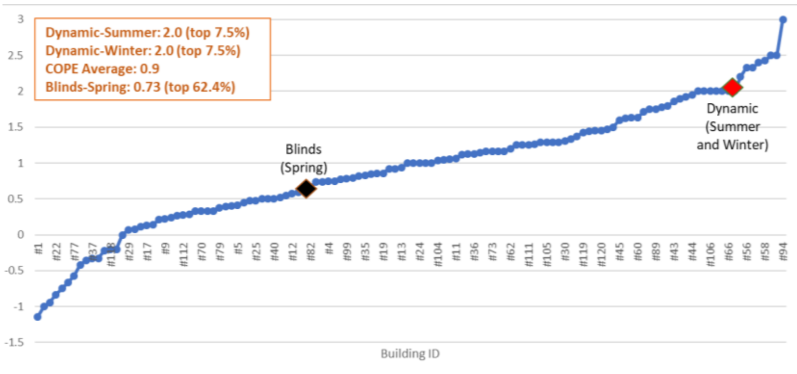
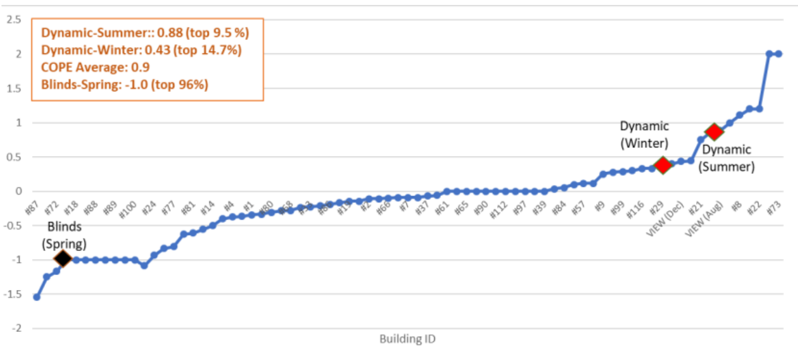
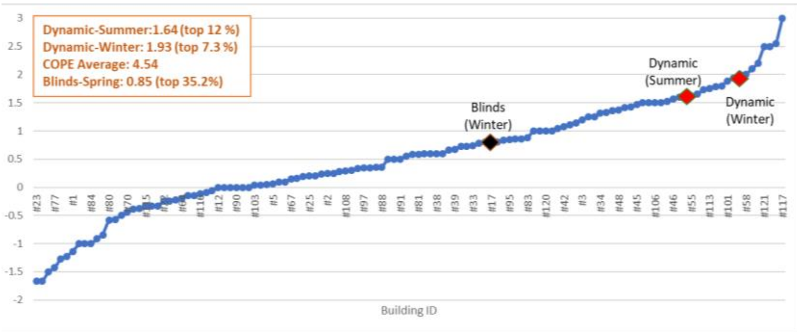
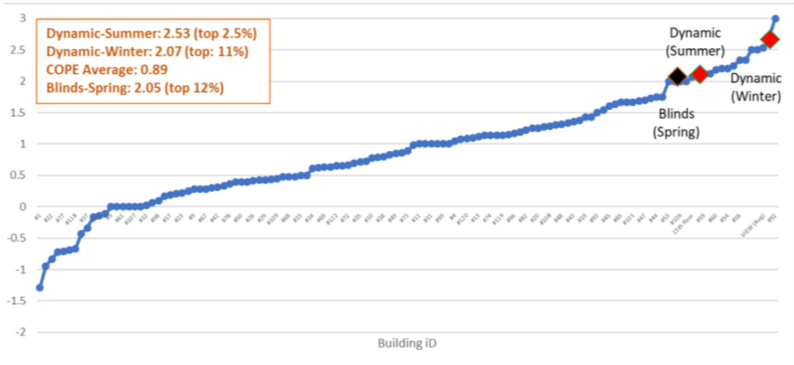
	COPE Database
Overall IEQ Satisfaction	
Overall Thermal Quality Satisfaction	

Table 10. *Cont.*

	COPE Database
Overall Visual Quality Satisfaction	
Job Satisfaction	

4. Conclusions

This pre- and post- study of 17 office workers moving from a mix of open and closed workstations in offices with manual blinds to a mix of open and closed workstations with dynamic glazing in the same office building, resulted in statistically significant improvements in user satisfaction with lighting; daylighting and view to outside; perceived health and productivity; and improved emotional responses.

Relative to environmental satisfaction, occupants in the office with dynamic glazing had 38% higher satisfaction with the quality of daylight, 33.8% higher satisfaction with overall lighting conditions, and 40.6% higher satisfaction with views to the outside compared to occupants in offices with manually controlled blinds (all p-values < 0.001*).

Relative to perceived health, occupants in offices with dynamic glazing (and corresponding glare control, daylight, and views) reported an average of 38% less frequent health symptoms of headache, thermal stress, distraction, tired eyes, drowsiness, visual discomfort on the computer screen, and annoyance from glare. Those occupants also reported an average of 26.4% greater sense of relaxation, satisfaction with a view to outside, and happiness (all p-values <= 0.055).

Relative to perceived productivity, occupants in offices with dynamic glazing (and corresponding glare control, daylight, and views) reported 29.4% greater perceived alertness (p-value < 0.001) and 17.2% greater perceived productivity (p-value = 0.055); 10 in 17 occupants in offices with manual blinds felt that glare made it hard to see their computer screens (59%), dropping to 4 in 17 or 24% in offices with dynamic glazing; 7 in 17 occupants on floors with manual blinds also tended to find that glare disrupted their concentration (41%) dropping to 2 in 17 (15%) in offices with dynamic glazing.

Relative to positive and negative emotional responses, occupants in offices with dynamic glazing reported 30% greater positive emotional responses of aroused, awake, energized, excited, delighted, happy, calm, relaxed, serene, comfortable, pleased, and bright, and 22% lower negative emotional responses, especially in tense, tired, dark, boring, sad, and gloomy, than occupants in offices with manual blinds, on average.

These gains were recorded even among workers moving from perimeter to core locations. Many of these gains might be attributed to the increased number of hours with clear views and glare-free daylight contributions enabled by dynamic glazing, as compared to manually controlled venetian blinds that were often left in predominantly closed conditions.

The results from the more widely used COPE survey revealed that the overall IEQ satisfaction, thermal quality, visual quality, and job satisfaction scores in offices with dynamic glazing are in the top 7.5% to 15% of a data set of 2300 workstations surveyed across North America in Carnegie Mellon's COPE database. On the other hand, occupants in offices with manual blinds in that same building reported measurably lower levels of satisfaction. Moreover, the COPE responses reveal that work environments with dynamic glazing significantly enhance satisfaction with lighting for paper and computer tasks, thermal comfort, visual comfort, personal productivity, and overall IEQ satisfaction internally consistent across two seasons (i.e., fall and winter).

Despite the statistically significant findings discussed above, there are still limitations to the research. A common challenge for research that uses these statistical analysis methods is that clearer and stronger results can be obtained with a larger number of subjects. Even though a total of 17 office workers in before and after work settings across three seasons is satisfactory for *t*-tests, that number is less adequate when it is subdivided into groups based on age, gender, and location. Another limitation is the lack of a control group who remained with manual blinds to test for a temporal trend in satisfaction; however, the multi-season follow up shows that changes in outcomes were immediate and sustained. This study also relied on subjective measures which may be biased by participants' lack of blinding to test conditions. Finally, there was a shift in the number of closed offices before and after, and in the net size of workstations, that could have affected the subjective responses. Surprisingly, subjective responses uniformly improved despite the potential loss of net square footage and perimeter closed office positions.

The nine-month comparative study of work environments in the offices demonstrated that the introduction of dynamic glazing, to replace conventional glazing with manual venetian blinds, results in statistically significant increases in environmental satisfaction, physiological responses related to health and productivity, and emotional responses to the perceived changes in light, glare, view and thermal conditions.

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