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Advancement of Electrochromic Windows final report

Summary results of visual comfort measurements at the electrochromic windows testbed

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1. Study Conditions

The study was performed at the Lawrence Berkeley National Laboratory (LBNL) windows testbed in Berkeley California. The location is 37.4°N latitude. The maximum solar altitude ranges from approximately 29° to 76°, with a yearly average of about 53°. The testbed rooms have their windows mounted due south. The azimuthal angle at sunrise varies from approximately 60° from due south in the winter to 120° in summer. The analysis was restricted to the period from 6:00-18:00 standard time. Sunrise ranges from 4:42 to 7:17 (solar time), so the sun was not visible during part of the winter study periods.

There are three rooms with windows in the testbed. Room A had standard windows with a fixed transmittance of 42%. Rooms B and C had electrochromic windows with a variable transmittance between approximately 5% and 60%. The measurements analyzed here were taken over the period from May of 2004 to July of 2005. 206 days were analyzed and were a representative sample, as they are fairly evenly distributed over the entire maximum solar altitude range from 29° to 76°.

A number of different test conditions were studied in each of the rooms. In room A, there were two main test conditions: dimmable electric lights set to maintain approximately 510 lux average, with (138 days) or without (65 days) Venetian blinds. For the conditions with blinds, the blinds were pulled down to cover the entire window, and the slats were fixed at 45° down (as viewed from inside). Sky conditions, were measured by maximum solar altitude, vertical and horizontal lux, and sky clearness calculated from a weighted average turbidity estimate (described later). The average horizontal illuminance was about 25% higher during the periods when the blinds were deployed, which is statistically significant. Both the average maximum solar altitude and average clearness (lower values of turbidity) were higher for the test condition with blinds, but these differences were not statistically significant for either of the variables by themselves. The other variables were not significantly different between the test conditions. The average maximum solar altitude value for the no blind test condition is one degree lower than the average expected over the year, while the blinds down condition is about 4° high. These differences are fairly small, which indicates that overall results for the two conditions should be comparable to results expected for a years worth of data. A summary of the sky conditions for room A for the two test conditions, their difference, and the probability that the difference is due to chance (where applicable), is shown in Table 1 below.

Rooms B and C were nominally identical, so the results from both rooms, after some adjustments (described later) are examined together. There were 359 valid data points, the bulk of which occurred in seven different test conditions. Table 2 lists these main test conditions, labeled A through G, along with the number of valid data points in each. Column 2, "Algorithm", describes the window transmittance control goal. Algorithm "D" maximizes daylight until the room reaches approximately 500 lux (electric lights off), and then limits the window transmittance to reduce glare and heat load. Algorithm "G" is a glare control mode, which darkens the window whenever the vertical illuminance on the plane of the window exceeded 30,000 lux. Algorithm "GP" is similar to "G", but the window only darkens if the profile angle is less than 75°, so that the sun penetrates more than 3 ft into the room. There are five rows of controllable windows. If no number precedes the control algorithm designation, than all rows are controlled the same. A designation of 1D or 2D indicates that the top row, or two rows are controlled to maximize daylight. The designation following the “&” gives the control mode for the lower rows.

The transmittance of the electrochromic windows was controlled either by the manufacturer’s supplied controller (ECmanuf), or by a controller built by LBL (EClbnl1). The electrochromic windows were tested with and without Venetian blinds. An entry of 0 in the percent shade column indicates that the blinds were all the way up, and did not block the sun. An entry of 100 indicates that the blinds were all the way down, and were tilted at a 45° down angle as viewed from the inside. In the split zone configuration, tests were run with the blinds covering just the window row that was controlled for daylight (20 or 40 percent). The tilt angle was again 45° down.

Table 1
Sky Conditions for Room A

	No blinds	Blinds	difference	Probability
Maximum solar altitude				
minimum	29.2	29.1	0.0	
maximum	75.6	76.1	-0.5	
average	51.7	56.8	-5.2	9%
Vertical Illuminance	26425	27418	-993	95%
Horizontal illuminance	23942	30118	-6176	0.2%
Average Turbidity	26	21	4.4	14%

Table 2
Test conditions and number of test values

Condition	Algorithm	Controller	Percent shade	Zones	# Rm B	# Rm C	Total
A	D	ECmanuf	0	0	28	54	82
B	D	ECmanuf	100	0	22	26	48
C	G	ECmanuf	0	0	47	41	88
D	1D&4G	ECmanuf	0	1	15	15	30
E	1D&4G	ECmanuf	20	1	13	14	27
F	1D&4GP	EClbnl1	20	1	11	17	28
G	2D&3GP	EClbnl1	40	2	18	9	27
Sum					154	176	330

In the initial studies with the ECmanuf controller, all the windows were controlled in an identical fashion. After a calibration check showed that some of the windows were no longer responding over the same range of transmittance, a new controller setup was installed (EClbnl1) to more closely control the windows to the same transmittance. The differences in absolute transmittance, and the rate of change in transmittance between different windows leads to some differences in the response of rooms B and C even when they are tested under what are nominally the same conditions. Results from 34 days when rooms B and C were tested under the same conditions were examined to determine the mean difference and variability in the difference between the two rooms. Differences were examined for the requested window transmittance, the fluorescent lighting contribution to horizontal illuminance, and all of the dependent lighting comfort/quality variables that were analyzed in the study. Columns two and three of Table 3 shows that the difference were in general fairly small, and reasonably precise. The horizontal max/min ratio is the most variable measurement. It depends on measurements at individual points in the room, and is therefore sensitive to differences in individual panes of the window, and particular solar and sensor positions. The other measures depend more on the aggregate properties of all 15 panes at once. Column 4 shows that most of the differences were statistically significant, even though they were small. Column 5 shows the standard deviations of the differences after fitting them against controller setup and the outdoor solar conditions (vertical illuminance and solar angle). Column entries marked “NS” indicate that the fit was not statistically significant. Column five is a measure of the precision of the differences measured between the test rooms and the reference room.

Table 3
Differences or ln(ratios) between rooms B & C under nominally identical conditions

Variable	*mean difference*	*standard deviation*	*Significance*	*Fit precision*
Cmd1	1.34	1.68	0.000	0.53
Cmd2	1.51	1.92	0.000	0.71
	mean ln ratio	standard deviation	Significance	Fit precision
Flwpl	0.054	0.095	0.002	0.061
Horz avg	0.071	0.146	0.007	NS
Horz max/min	-0.015	0.258	0.743	NS
DGI window	-0.025	0.015	0.000	NS
DGI east	0.084	0.021	0.000	NS
DGI-90°	-0.054	0.032	0.000	NS
LR West W	-0.008	0.018	0.015	0.016
LR-Win W	-0.055	0.087	0.001	0.057
LR East W	0.131	0.037	0.000	0.025
BL prob	*-0.017*	*0.041*	*0.024*	*0.028*

Notes:
Cmd1: The transmittance requested by the controller for the entire window when it is controlled as a unit, or the lower rows when it is controlled in two zones.
Cmd2: The transmittance requested by the controller for the upper window zone.
Flwpl: The calculated horizontal illuminance contribution of the fluorescent lights.
Horz avg: The average of six horizontal oriented illuminance sensors placed evenly through the room.
Max/min: The maximum to minimum ratio for the above six sensors.
DGI window: The computed weighted average disability glare index over the day for a subject facing the window [1].
DGI east: As above, for a subject facing the east wall.
DGI-90°: As above, for glare from the window while facing west.
LR West W: The luminance ratio between the average luminance on the west wall, and the remaining field of view facing west.
LR-Win W: As above, for a subject facing the window.
LR East W: As above, for a subject facing the east wall.
BL prob: The computed average probability that the a person would want to lower the blinds given the luminance of the window (this probability has a minimum of 10 %) [2].

The values for rooms B and C were corrected to the mean value for the two rooms, using the direct ratios or fits mentioned in Table 3. As noted this is generally a fairly small correction. A more important issue is that there is a fairly limited number of points for each test condition (the last column of Table 2), so the points are, at best, just a sample of the conditions expected over the year. In Table 4, the minimum, mean, and maximum noon-time solar altitudes are listed for each of the test conditions. Test conditions A through C include data over the range of solar altitudes possible for the site. The mean noon solar altitude for these three conditions is lower than expected yearly average (about 53°), but is close. The mean noon solar altitudes for test conditions D and E are only slightly higher than the expected yearly average, but they lack any winter data, and cannot be considered representative of a full years data. Test conditions F and G only covered summer conditions.

Table 4
Noon-time solar angles

Condition	Minimum	Mean	Maximum
A	29.2	49.9	75.0
B	29.1	47.3	75.9
C	29.1	50.2	75.6
D	40.8	55.5	70.8
E	45.5	58.2	70.3
F	72.4	74.9	76.0
G	72.0	75.2	76.1

Table 4 is unfortunately not the entire story. Examination of the distributions of the data points for conditions A - C show that the number of spring and fall points is very sparse. Summary measurements or comparisons of visual comfort may not be valid if they are affected by the distribution of conditions, and not just the range and mean. As much as possible, the measures of visual comfort have to be fit as a function of solar angles and luminance conditions, to insure that comparisons are valid.

The fits cannot capture all the sources of variation, so to reduce the error in the comparisons, it is generally better to fit the differences between the test rooms and the reference room, rather than directly fitting each condition separately. There are two comparisons that can be made: those against the reference no blind condition, and those against the reference full blind condition. As there is only one reference room, data for any given day can only be compared to one reference condition. This unfortunately reduces the number of data points for the comparisons, and can reduce the range of sky and solar conditions. For condition A, there was no significant difference in the sky and solar conditions for the blind and no blind tests. All but one data point for condition B was tested against the full blind reference condition. Condition C, unfortunately, did show a significant difference in the sky and solar conditions between the two reference cases. Conditions A and B provide the most robust comparison data. The accuracy of all other comparisons are limited by the range of conditions studied.

In addition to the illuminance and comfort measures described above, the study also examined power use. The lighting system in each room consisted of 4 dimming electronic ballasts driving 8 lamps. The ballasts have an almost linear power versus voltage response for control voltages in the range from 1.0 to 6.5 V. The measured maximum power in each room at 6.5 V ranged from 271 to 272 W. The measured minimum power at 1 V ranged from 95 to 99 W. The minimum and maximum average room light levels were approximately 70 and 700 lux, respectively. There were no calibration measurements between 0.5 V and 1 V, and lamp operation in this range is assumed to be unstable. At 0.5 V the system is in a standby mode with no light output. The wattage in the standby mode is 25 W. The steady-state control voltage during normal operation of the system never exceeds a bit above 5 V, so system operation much above this range is irrelevant.

The average lighting power of the system depends upon the fraction of time that it spends in each of the operational modes (standby power, minimum power, and dimming range) and the average power in the dimming range. These factors in turn depend on the daylighting conditions and the choice of control algorithm. Different control algorithms handle the gap in available light outputs from 0 to 70 lux in different ways. One option is to never go below 70 lux. The second option is to allow the system to switch between 0 and 70 lux, but put in a time delay to eliminate "hunting" behavior which would be extremely irritating to the occupant. The time delay need not be the same for the two switching directions. For the period between 6:00-18:00 the lighting systems with the electrochromic windows averaged from 35 to 65 percent of their time at 100 W or less. The maximum possible average difference between different control algorithms is therefore 25 to 45 W (≈70 W x 35-65%). This is 9 to 17 percent of full power, and up to almost 40 percent of observed average power. This shows that specification of the control algorithm can have a major effect on the energy consumption of the system.

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Validation tests of the system were performed by running the two test rooms with the same window and lighting control algorithms. Wattages were sampled once per second, and averaged over a minute period. Control voltages were sampled once per minute. The rooms spent the same amount of time and used the same average power in the dimming range (within the estimated uncertainty of the values). Neither room spent any appreciable time at the actual minimum power level, presumably because they both exhibited "hunting" behavior, where the control system switches back and forth between minimum and standby power levels in an unsuccessful effort to satisfy the control goals. Both rooms did spend an appreciable fraction of their time at the standby power level, however neither the fraction of time spent at standby, nor the average power level between standby and minimum, were the same in the two rooms. Control voltages during the non-dimming period ranged from 0 to 1.0 V, and it appears likely that the systems were operating in an unstable manner. The data in this range is therefore not reliable, and direct calculation of overall average wattage for the control system we used was therefore not appropriate. The preliminary analysis instead assumes a control system which is restricted to the range from 1.0 to 6.5 V, and does not switch from minimum power to standby mode. Average overall power was calculated assuming that power level was 97 W when the system was not actively dimming.

2. General Results

As noted earlier, the sky conditions for both the two test conditions for the reference room span the likely conditions for a year. Summary measures for the independent variables measured under the reference conditions therefore provide useful information about which variables are significant in terms of lighting quality or energy use. Table 5, below, lists each of the variables examined, along with the summary measure examined, and a conclusion as to whether the variable was of interest. Most of the variables in Table 5 have already been described in the note to Table 3. The few that haven't been previously described are described in the note following the table.

Table 5
Dependent variable results for Room A

Variable	measure	no blinds	blinds	Comment
Flwpl	Mean	158	252	significant
Horz avg	Max	4230	1284	significant
	Mean	1749	717	significant
Horz max/min	Max	6.9	2	marginal
	Mean	3.1	1.5	not important
percent < 500 lux	Max	46%	84%	not important
	Mean	10%	15%	not important
amount < 500	Max	186	138	noise
	Mean	19	18	not important
DGI window	Max	24.9	21.0	significant
	Mean	21.9	18.1	significant
DGI east	Max	16.6	10.9	not important
	Mean	11.0	9.6	not important
DGI-90°	Max	16.0	11.8	not important
	Mean	12.9	9.0	not important
LR West W	Max	1.4	1.3	not important
	Min	0.9	1.2	not important
LR-Win W	Max	38.9	9.7	significant
	Mean	12.3	6.4	significant
LR East W	Max	1.24	1.17	not important
	Min	0.87	1.07	not important
% window lum >3000 cd/m^2	Max	52%	5%	significant
	Mean	16%	0%	significant
BL prob	Max	62%	37%	significant
	Mean	40%	18%	significant

Notes:
percent < 500 lux: The percent of time that the average of the 6 horizontal sensors was less than 500 lux.
amount < 500 lux: Average amount by which the average was less than 500 lux.
% window lum > 3000: Percent of time that the window luminance exceeded 3000 cd/m^2.

The main reason that variables are listed as not important is that they are within the normal guidelines for comfort or quality, even for the case where the blinds are left up. For discomfort glare (DGI), values of 16 in a non daylit room, or 20 in a daylit room, are considered to be "just acceptable". The computed DGI values from the east wall facing east, and from the window while facing west, barely exceed 16 even with no blinds drawn, and so are not a problem. Similarly, luminance ratios of 3:1 (1/3:1) and 10:1 (1/10:1) are considered to be standard guides as to what is acceptable in order to limit transient adaptation problems. The luminance ratios for the east wall to its background and for the west wall and its background are far below these limits, and therefore do not present a visual quality problem in either of the reference case conditions. Large variations in horizontal illuminance present problems of gloom, excessive brightness, or inadequate illuminance over some areas of the room. A max to min ratio of 2:1 is difficult to perceive if there are no sharp shadows, and it seems likely that a 3:1 ratio will not generally be viewed as excessive in a daylit space. A maximum to minimum ratio of 7:1 should be easily visible, and could conceivably result in negative perceptions of the space.

The electrochromic windows have a somewhat higher maximum transmittance than the reference window, so it is possible, though unlikely, that some of the above measures might be important in the test rooms. The electrochromic window test rooms are not more likely to have problems with the overall illuminance dropping below 500 lux. The maximum deficits recorded occurred for a single minute in a series of otherwise reasonable levels. Only two instances (minutes) of such deficits were recorded over 200 days worth of data. These were instrumental noise problems, and are not related to the window type. Smaller deficits, on the order of 10 to 30 lux, occurred whenever there were dark skies, and were very common doing winter test periods. These deficits were due to the fact the illuminance was controlled by a ceiling mounted sensor that records a slightly different illuminance than the average of the six horizontal mounted sensors in the room. The deficit is not large enough to cause any visual quality problems.

Both the average contribution of the fluorescent light to the workplane illuminance, and the average horizontal illuminance (lights and window), affect the amount of energy used by the space. The average maintained fluorescent light levels in both the blind and no blind condition are substantially below the nominal target level of 500 lux. The no blind condition saves about 100 lux relative to the blind condition. The fluorescent light levels in the reference conditions provide target values that the electrochromic windows should meet or exceed.

Small increases in the average horizontal illuminance level may actually improve visibility and visual quality, but large increases may degrade visual performance and increase cooling loads and thus energy use. With the blinds drawn the average horizontal illuminance is only 50% higher than the target 500 lux value, which is likely to be neutral or a net benefit. The luminance off a 50% reflective desk illuminated to 1300 lux is only about 200 cd/m^2, which is about the luminance from the white portion of the flat screen monitor in the room. The maximum illuminance from the blinds drawn condition is therefore not likely to degrade visual performance, but it is also probably beyond the point of improving performance, and it quite clearly is an increase in thermal load. The maximum illuminance measured in the no blind condition, 4230 lux, can lead to desk luminance levels that exceed the monitor luminance by over a factor of 3, and thus can cause a significant decrease in visual performance due to transient adaptation. It may lead to complaints of excessive brightness, and clearly represents a significant increase in thermal load.

The remaining factors all reach levels which indicate potential problems with visual comfort or quality. The DGI values in the table were derived from weighted daily averages, where the weighting is larger for large DGI values than for small ones (see appendix). The weighting means that isolated unacceptable levels of glare will result in a large, but not necessarily unacceptable glare rating for the day. For daylit spaces, glare becomes perceptible when DGI reaches 16, unacceptable when it reaches 20, uncomfortable at 24, and intolerable at 28 [3]. With the blinds down, the average glare rating is perceptible, but still acceptable. The worst day, however, while not uncomfortable, is above the acceptable range. This indicates that on the brightest day the blind tilt angle should be fully closed, instead of 45°. The situation is much worse with the blinds open. The test rooms all have large south windows, which makes for a significant glare potential. The average glare rating with blinds open is worse than the maximum glare rating with the blinds down. The maximum glare rating with the blinds up is past unacceptable and into the uncomfortable range.

The luminance ratios analyzed were the average values over the day, for each of the days in the study. When the blinds were drawn, the values exceeded the recommended ratios for a task against its immediate surround, but were within the acceptable range for a task against a background of possibly 30° or more from the line of sight. It would not be recommended that a person face the blinds while sitting near the wall. A side orientation would be acceptable even under the worst condition measured. When the blinds are up the average ratio exceeds the recommended level for a background view. A side view would still be acceptable if the person is located far enough back from the window that it becomes a more remote (on the order of 60° from the line of sight) portion of the background. Locations nearer the window may degrade the visibility of the tasks.

During the course of an earlier human subject study in the electrochromic testbed it was found that the probability that subjects would pull the blinds was strongly correlated to the average luminance of the window [4]. Three-fourths of the subjects pulled the blinds by the time the luminance reached 3000 cd/m^2. A logistics function fit the probability data well for probabilities above 15 percent, which appears to be the approximate minimum probability for normal day time luminances. If the blinds are already down, then a luminance above 3000 cd/m^2, or a probability above about 20%, suggests that the blinds have to be closed more to control the luminance. Only a few percent of the cases exceeded 3000 cd/m^2, and only about 20% exceeded a blind probability of 20%, so the 45° tilt-blind down position was suitable for most situations. The blind-up case was too bright for almost half the days, as judged by the predicted number of subjects who would pull the blinds.
The power data that was analyzed was the fraction of time in the dimming mode, f, and the average power in the dimming mode, p_d. Overall average power, $\langle p \rangle$, is the weighted average of the average power in the dimming mode

and the minimum power, p_m (p_m = 97 W):

$\langle p \rangle = p_d * f + p_m * (1 - f)$.

The data was correlated against solar altitude, $Ø_S$, average vertical, E_v, and horizontal lux, E_h, and average extraterrestrial horizontal average ($\sin(Ø_S)$ x direct normal sun illuminance), E_a. The results are presented in terms of the fits, and as estimated average values for a year, based on average values of the independent variables of the fits:

Table 6
Average yearly values of independent variable

Variable	Value
E_a	65800
E_v	28500
E_v^2	1.008×10^9
E_h	27100
E_h^2	8.998×10^8
$Ø_s$	53.0
$Ø_s^2$	3080

In the reference room the window transmittance is fixed at 40%, and the room was run with blinds down at 45° tilt, or with blinds up. The absolute power data was fit directly to sky conditions:

$\% \text{ dim} = a + b \times E_v + c \times E_h + d \times E_h^2 + e \times Ø_S + f \times Ø_s^2$
where the constants are given in Table 7.

Table 7
Fit constants for calculating the percent time lamps are being dimmed in reference room

Constant	No blinds	Blinds
a	1.2781	1.3114
b	-3.780×10^{-6}	-1.514×10^{-5}
c	-3.773×10^{-5}	-1.353×10^{-6}
d	5.243×10^{-10}	7.575×10^{-11}
e	-0.01069	-0.01069
f	1.146×10^{-4}	1.146×10^{-4}

The average estimated dimming percentage for the full year are 40.5% and 69.8% ± 5.2% with no blinds and blinds respectively.

$\langle \text{dimmed power} \rangle = a + b \times E_a + c \times E_h + d \times E_v + e \times E_v^2$
where the constants are given in Table 8.

Table 8
Fit constants for calculating dimmed power in the reference room

Constant	No blinds	Blinds
a	222.53	231.73
b	-6.304×10^{-4}	-3.494×10^{-4}
c	$=1.047 \times 10^{-3}$	-5.976×10^{-4}
d	5.345×10^{-4}	-1.508×10^{-3}
e	5.242×10^{-10}	2.919×10^{-8}

The average estimate power in the dimming range for the full year are 168.3 and 179.0 ± 3.6 W with no blinds and blinds respectively. The overall average power for the year are 125.8 ± 4.0 and 154.2 ± 4.9 W for no blinds and blinds respectively.

3. Results in the Test Rooms

3.1. Illuminance and visual comfort measures

Direct comparisons between the test and reference conditions can be made either by taking a difference or a ratio. In a preliminary stage of the analysis, it was found that both fits were about the same in terms of their statistical significance. The difference fits, however, were much easier to analyze and understand. The final analysis was therefore performed in terms of differences.

As noted earlier, none of the conditions studied covered an entire year. This means that simple differences between the test and reference conditions may not be representative of performance over a full year. To correct for this problem, an attempt was made to fit each of the dependent variables as a function of independent variables that vary in a known or easily fit manner over the year. All of the dependent measures should have some relationship to the vertical and horizontal illuminances. Some of the variables may also depend significantly on the sun geometry during the day. We used the daily average vertical illuminance on a south facade, the daily average horizontal illuminance, and the noon-time solar altitude, plus combinations of these variables, in fits of each of the dependent variables. We then fit the vertical and horizontal illuminance variables at the testbed as functions of solar altitude. Table 9 lists each of the independent variables and their mean yearly values.

Table 9
Yearly mean values of the independent variables

Variable	mean
noontime solar angle	53.0
vertical lux	28,500
horizontal lux	27,100
altitude*Ev	1,450,000
vertical^2	1.01E+09
vertical*horizontal	8.18E+08

The mean yearly values in Table 9 were used to adjust the measured differences to yearly averages. Tables 10 through 16 list each of the dependent variables and the calculated differences. The conditions are listed in the first column, while the differences versus the no-blind, and blind down reference window are listed in columns two and three. Column 4 gives an uncertainty estimate for the differences. Differences that are likely to be significant (approximately twice the uncertainty estimate) are marked in bold. For two of the dependent variables there was no reasonable fit possible for conditions F and G, and these entries are marked as NF (no fit).

Table 10
Fluorescent workplace illuminance

Condition	No blinds	Blinds	Uncertainty
A	-20	**-129**	15
B	**67**	-6	16
C	**100**	27	15
D	-7	**-80**	21
E	**76**	3	21
F	NF	NF	NF
G	NF	NF	NF

Table 11
Average Horizontal workplace illuminance

Condition	No blinds	Blinds	Uncertainty
A	**-885**	167	151
B	**-849**	-88	199
C	**-962**	-38	153
D	**-1150**	282	184
E	**-1184**	3	188
F	**-1138**	-160	317
G	**-1116**	-127	512

Table 12
Horizontal maximum/minumum ratio

Condition	No blinds	Blinds	Uncertainty
A	0.56	**2.1**	0.51
B	-1.05	0.06	0.62
C	-0.19	1.06	0.61
D	-1.31	**2.06**	0.71
E	**-2.39**	**1.35**	0.64
F	-1.23	0.12	1.13
G	-1.01	0.31	1.86

Table 13
Average window DGI

Condition	No blinds	Blinds	Uncertainty
A	**-1.97**	**1.69**	0.78
B	**-5.58**	**-1.92**	0.81
C	**-2.68**	0.98	0.78
D	**-2.86**	0.8	0.95
E	**-2.22**	1.44	0.96
F	-2.1	1.55	2.47
G	-5.89	-2.23	3.1

Table 14
Luminance ratio: window/surround

Condition	No blinds	Blinds	Uncertainty
A	**-2.24**	**3.29**	1.07
B	**-7.14**	-1.61	1.15
C	**-3.11**	**2.42**	1.07
D	**-5.02**	0.51	1.54
E	**-3.27**	2.26	1.57
F	-3.03	2.5	4.25
G	-8.49	-2.96	5.1

Table 15
Percent time Luminance > 3000 cd/m^2

Condition	No blinds	Blinds	Uncertainty
A	**-16%**	0.10%	4%
B	**-16%**	0.00%	4%
C	**-16%**	0.10%	4%
D	**-16%**	-0.50%	4%
E	**-16%**	-0.20%	4%
F	**-16%**	0.00%	4%
G	**-16%**	0.00%	4%

Table 16
Probability of pulling blinds

Condition	No blinds	Blinds	Uncertainty
A	**-18%**	2%	3%
B	**-33%**	-5%	3%
C	**-23%**	-2%	3%
D	**-26%**	1%	4%
E	**-24%**	1%	4%
F	NF	NF	NF
G	NF	NF	NF

In all the above difference tables, the differences are computed as the test (electrochromic) window value minus the reference window value. Thus, for example, in Table 10, the negative value for condition A versus the reference window with blinds, means that fluorescent light usage was lower in the test room than in the reference room.

In general, the trends are what one expects, it is only a question of the magnitudes of the effects that is of interest. For fluorescent light use, condition A: daylight harvesting and no blinds, and condition D: split mode and no blinds, require less fill light than the reference window with blinds, and are roughly equivalent to the reference window with blinds. Condition B: daylight harvesting with blinds down, condition C: glare mode control with blinds up, and condition E: split mode with blinds over the daylight harvesting pane, require approximately the same amount of fill light as the reference window with the blinds down, and significantly more fill light than the reference window with the blinds up.

All the electrochromic window test conditions resulted in significantly lower average horizontal illuminance levels. This potentially could lead to significant cooling load savings. An examination of the distribution of the actual levels showed a maximum level of under 2000 lux for the two daylight harvesting modes without blinds. This is not so high as to be likely to cause significant visual performance degradation.

The extreme values of the max/min ratio are determined by sunlight penetration, and were not reduced by the electrochromic windows. Except for condition E (split mode with partial blinds) there was no significant improvement in the average max/min ratios found versus the reference window without blinds. Three of the modes: A, D, and E, were significantly worse than the reference window with blinds. As noted earlier, the general level of the max/min ratio was not of major concern, and the extreme values were of only marginal concern. Electrochromic windows do not appear to offer any significant improvement in this metric, but it is not a metric of major significance.

All of the electrochromic test conditions show an improvement in glare relative to the reference window with no blinds, and in the five conditions (A - E) where there is a reasonable range of sun angles, the improvement is statistically significant. The improvement is least for where the window is only controlled for daylight and has no blinds (condition A). The mean glare in this condition is in the acceptable range, and there are no longer any days in the uncomfortable range, but there are days in the unacceptable range (20 - 24). Condition A is significantly worse than the reference window with blinds. Condition B, which is a daylight harvesting mode with the blinds drawn, shows the most improvement, and in fact maintains glare in the acceptable range even on the worst days. Conditions C through E are intermediate in performance. They still permit unacceptable glare on the worst days, but the increase in glare relative to the reference window with blinds was not statistically significant.

A very similar pattern is evident in the window wall to background luminance ratio results. For conditions A, C, and E, only the worst case values exceeded a 10:1 ratio. For conditions B and D, even the worst case values were below this limit. Conditions B, D, and E gave results that were similar to reference window with the blinds down.

The electrochromic windows in all 7 modes of operation were capable of reducing the average fraction of time that the window exceeded 3000 cd/m^2 to almost zero. For condition A, in 10% of the test days the window luminance exceeded 3000 cd/m^2 for 2% or more of the time. On the worst day the exceedance was for almost 10% of the time. The average percentage of time over all days that the windows exceeded 3000 cd/m^2 was about 0.5%. Condition A was the worst case. Condition C, the next worst case, had a worst day exceedance of 5%. For the remaining conditions the maximum was under 1% (7 minutes of the day).

Table 16 shows that the control of window luminance by the electrochromic windows, as measured by the logistic blind probability function, is not significantly different from the reference window with the blinds already pulled.

3.2. Power use

The fits for power use are listed in the tables below. There was insufficient data to provide reasonable fits for the dimming probability for conditions F and G, and there was essentially no data for the no blind condition comparison for condition B. These fits were left blank:

% dim difference = $a + b \times E_v + c \times Ø_S$
where the constants for the 7 conditions are given in Table 17 below.

Table 17
Constants for power difference fit

Condition	No blinds	Blinds
Constant a:		
A	0.02438	0.2682
B		0.1562
C	-0.1081	0.1168
D	-0.2407	-0.9355
E	-1.0595	-2.3872
Constant b:		
A	$2.123\text{x}10^{-6}$	$2.123\text{x}10^{-6}$
B		0
C	$1.169\text{x}10^{-5}$	$1.169\text{x}10^{-5}$
D	$1.0676\text{x}10^{-6}$	$1.3661\text{x}10^{-5}$
E	$6.3625\text{x}10^{-6}$	0.00003603
Constant c:		
A	-0.003013	-0.01283
B		-0.005045
C	0.0004073	-0.008343
D	0.005394	0.005394
E	0.02383	0.02383

The computed annualized differences in the fraction of time in the dimming mode are listed in Table 18.

Table 18
Annualized difference in time spent in the dimming mode

Condition	No blinds	Blinds
A	-0.065	-0.358
B	0.176	-0.117
C	0.273	-0.02
D	0.05	-0.243
E	0.244	-0.049

The annualized differences for conditions C & E with blinds are not significantly different from zero. The remaining differences were significant at the 1% probability level or better.

The fit for the difference in average power in the dimming mode is:

<dimmed power difference> = a + b x E_h + c x E_v

where the constants for the 7 conditions are given in Table 19 below.

Table 19
Constants for calculating power difference in dimming mode for 7 EC control conditions

Constant a:		
Condition	No blinds	Blinds
A	-10.05	-21.847
B	5.315	-6.482
C	-12.505	-24.302
D	16.333	4.536
E	-5.016	-16.813
F	-45.815	-57.612
G	-4.652	-16.449
Constant b:		
Condition	No blinds	Blinds
A	4.809×10^{-5}	-4.188×10^{-4}
B	4.670×10^{-4}	7.720×10^{-8}
C	1.757×10^{-3}	1.290×10^{-3}
D	-6.828×10^{-4}	-1.150×10^{-3}
E	8.906×10^{-4}	4.238×10^{-4}
F	-7.775×10^{-4}	-1.244×10^{-3}
G	-6.828×10^{-5}	-5.352×10^{-4}
Constant c:		
Condition	No blinds	Blinds
A	3.854×10^{-5}	4.774×10^{-4}
B	-3.377×10^{-4}	1.011×10^{-4}
C	-1.178×10^{-3}	-7.397×10^{-4}
D	-3.521×10^{-4}	8.668×10^{-5}
E	-1.109×10^{-3}	-6.703×10^{-4}
F	4.092×10^{-3}	4.531×10^{-3}
G	4.777×10^{-4}	9.166×10^{-4}

The calculated annualized differences in average power in the dimming mode are given in Table 20.

Table 20
Annualized differences in average dimmed power

Condition	No blinds	Blinds
A	-8.4	-19.1
B	7.1	-3.6
C	1	-9.7
D	-13	-23.7
E	-13.4	-24.1
F	48.6	38
G	6.1	-4.5

The four cases which are significantly different from zero are underlined. Table 21 shows the calculated annualized average difference in overall power as expressed as percentage of the annualized overall power in the reference condition. Statistically significant differences are again underlined.

Table 21
Percent differences in annualized power

Condition	No blinds	Blinds
A	-6%	-23%
B	13%	-8%
C	16%	-5%
D	-2%	-20%
E	7%	-13%

There is a fairly clear general trend of energy savings versus the reference window with blinds, and no energy savings or even a loss versus the reference system with no blinds.

3.3. Mixed conditions

None of the seven conditions is optimal from a joint visual quality and power saving perspective. However, one of the points of the electrochromic window system is that it can be controlled in different ways. A review of the visual quality data by time of year suggested that from April to September the Electrochromic system could provide adequate levels of visual quality with the blinds up. From mid-November to mid-January the blinds needed to be fully deployed, and for the remainder of the year, the blinds could be deployed over just the top row of the windows. For comparison, the reference window needs the blinds all year long. Condition B, was the only condition with the blinds all the way down. Conditions A, C and D, had the blinds all the way up. Conditions E and F had the blinds across just the top row. Condition F, which had the blinds across two rows, was treated the same as E and F. Tables 22 through 31, below, repeat the analyses for the annualized values for the set of mixed conditions that fit the constraints suggested by visual quality data. Statistically significant results for are bolded.

Table 22
Fluorescent light use difference

	no blinds	blinds	SE
A + B	9.7	**-87.8**	11.2
C + B	**88.2**	15.1	11.2
D + B	**29.6**	**-43.5**	13.6
B + A + E	6.4	**-91.2**	10.8
B + C + E	**84.8**	11.7	10.8
B + D + E	26.2	**-46.9**	13.4

Table 23
Horizontal workplace illuminance difference

	no blinds	blinds	SE
A + B	-881	32	125
C + B	**-912**	-65	125
D + B	**-997**	112	136
B + A + E	**-987**	58	105
B + A + F	**-999**	-19	132
B + C + E	**-1017**	-39	105
B + C + F	**-1030**	-117	133
B + D + E	**-1103**	139	118
B + D + F	**-1116**	61	143

Table 24
Horizontal illuminance max to min ratio difference

	no blinds	blinds	SE
A + B	-0.33	**1**	0.4
C + B	-0.7	0.48	0.44
D + B	**-1.22**	**1.06**	0.48
B + A + E	-0.7	**1.46**	0.35
B + A + F	-0.57	0.84	0.46
B + C + E	**-1.06**	**0.94**	0.39
B + C + F	-0.94	0.32	0.49
B + D + E	**-1.59**	**1.51**	0.44
B + D + F	**-1.46**	0.9	0.53

Table 25
DGI window difference

	no blinds	blinds	SE
A + B	**-3.18**	0.48	0.58
C + B	**-3.49**	0.17	0.58
D + B	**-3.54**	0.12	0.64
B + A + E	**-2.48**	**1.18**	0.54
B + A + F	**-2.56**	1.1	0.9
B + C + E	**-2.79**	0.87	0.54
B + C + F	**-2.87**	0.79	0.9
B + D + E	**-2.83**	0.83	0.61
B + D + F	**-2.91**	0.74	0.94

Table 26
Window luminance ratio difference

	no blinds	blinds	SE
A + B	**-3.78**	**1.75**	0.79
C + B	**-4.13**	1.4	0.79
D + B	**-5.24**	0.3	0.99
B + A + E	**-3.22**	**2.31**	0.78
B + A + F	**-3.33**	2.2	1.47
B + C + E	**-3.56**	**1.97**	0.78
B + C + F	**-3.68**	1.85	1.47
B + D + E	**-4.67**	0.86	0.97
B + D + F	**-4.79**	0.74	1.59

Table 27
L > 3000 cd/m^2 difference

	no blinds	blinds	SE
A + B	**-0.159**	-0.001	0.028
C + B	**-0.159**	0	0.028
D + B	**-0.151**	0.008	0.028
B + A + E	**-0.164**	-0.005	0.025
B + A + F	**-0.159**	0	0.025
B + C + E	**-0.163**	-0.005	0.025
B + C + F	**-0.158**	0	0.025
B + D + E	**-0.155**	0.003	0.025
B + D + F	**-0.15**	0.008	0.025

Table 28
Change in probability of demand for blinds

	no blinds	blinds	SE
A + B	**-0.233**	0.009	0.02
C + B	**-0.263**	-0.014	0.02
D + B	**-0.287**	-0.007	0.024
B + A + E	**-0.21**	0.02	0.019
B + C + E	**-0.24**	-0.003	0.019
B + D + E	**-0.265**	0.004	0.023

Table 29
Change in percent savings during dimming

	no blinds	blinds	SE-blinds	SE-no blinds
A + B	-2.00%	**-7.90%**	2.40%	2.30%
C + B	**6.60%**	0.30%	2.50%	2.30%
D + B	-5.00%	**-10.60%**	3.10%	2.90%
B + A + E	**-7.10%**	**-12.60%**	2.40%	2.30%
B + A + F	**10.90%**	4.30%	4.90%	4.60%
B + C + E	1.60%	-4.50%	2.40%	2.30%
B + C + F	**19.60%**	**12.40%**	4.90%	4.60%
B + D + E	**-10.10%**	**-15.40%**	3.10%	2.90%
B + D + F	7.90%	1.50%	5.30%	4.90%

Table 30
Change in dimming probability

	no blinds	blinds	wt. Unc.
A + B	0.70%	**-28.60%**	1.20%
C + B	**19.50%**	**-9.80%**	1.70%
D + B	**16.10%**	**-13.20%**	1.50%
B + A + E	-4.20%	**-33.50%**	2.60%
B + C + E	**14.50%**	**-14.80%**	2.90%
B + D + E	**11.20%**	**-18.10%**	2.80%

Table 31
Percentage of overall power difference (assuming minimum power = 98 W)

	no blinds	blinds	SE-blinds	SE-no blinds
A + B	-0.70%	**-18.90%**	4.60%	3.80%
C + B	**16.40%**	-5.00%	5.40%	4.40%
D + B	5.40%	**-14.00%**	4.90%	4.10%
B + A + E	-5.80%	**-23.10%**	4.20%	3.50%
B + C + E	9.40%	**-10.70%**	4.90%	4.00%
B + D + E	-0.60%	**-18.90%**	4.50%	3.70%

4. Discussion

When only one condition for the year is considered, condition B is the clear winner in terms of the visual quality metrics, especially with respect to DGI and window luminance ratios, but it offers marginal lighting energy savings compared to the reference case of a simple window with blinds drawn. The two other conditions which do appear to offer lighting energy savings relative to this reference case are conditions A and D. Condition A offers the best savings, but visual quality is significantly worse in this case than for the comparison reference case. Condition A does provide better visual quality than the reference window without blinds, but it doesn't provide lighting energy savings versus this case. The data suggests that condition D may be somewhat worse than the reference window with blinds in terms of visual quality, but only the decrease in performance for the horizontal maximum to minimum ratio was statistically significant in our data set. This condition is at least close to the blinds down reference condition in visual quality, while actually saving some lighting energy. The results for condition E appear somewhat anomalous. Lighting energy use was higher than for condition D, and uniformity was better. However, there did not seem to be an improvement in the visual quality metrics of DGI and window wall luminance ratios. This may be due to the small sample sizes, as these metrics are not significantly different between the two rooms. Condition C, which used a glare mode for all 5 windows, but no blinds, appeared to require approximately as much lighting energy as the reference blind down condition, while giving visual quality in between the reference blind down and blind up conditions. Its sole advantage over the reference blind down condition is that it permits a view.

We had insufficient data to make firm predictions about conditions F and G. However, on a strictly physical basis, they should give visual quality performance that is comparable to, or better than, conditions D and E. They both saved lighting energy relative to the reference blind down condition during the summer, but it is not known at this time whether this conclusion is valid for the year as a whole. These lighting energy savings were at the expense of somewhat higher window luminances than the reference conditions with the blinds down, but again it is not known how the windows would compare over the whole year.

The situation for the mixed condition cases is clearly better. For the conditions where we have sufficient information to make annual estimates, all but the B + C condition saved a statistically significant fraction of energy relative to the blinds down condition. Visual quality is mostly comparable to that of the blinds condition. For the metrics where it is worse, the differences appear to be of minimal practical significance. The max/min ratio for horizontal illuminance is significantly higher than the reference-blinds down case for several conditions, but is still within the 3:1 ratio which might cause some problems. The luminance ratio for the window wall is also significantly higher in some cases, but again remains below the 10:1 ratio that is considered acceptable for a background that is not immediately adjacent to the task.

The failure of the electrochromic windows to adequately control glare as measured by DGI was disappointing, but not unexpected. What was unexpected, was that examination of the DGI values versus time and window transmittance indicated that at least some of this failure was due to a failure of our glare control algorithm, and not the electrochromic window itself. Significant amounts of glare occurred during some early morning periods when the window was still fully transparent.

5. Conclusions

Electrochromic windows offer the possibility of a higher use of daylight than normal windows which always have the blinds drawn, while at the same time providing better comfort than normal windows with the blinds up. However, even when window blinds are drawn a significant amount of light enters through the window, and lighting energy savings are not as easy as might be thought. For the five conditions for which there was sufficient data for good comparisons, only the two conditions with at least a portion of the window being unshaded and operating in a daylight harvesting mode, and the blinds down with full daylight harvesting, saved energy relative (on an annualized basis) to the reference blind condition. The remaining two conditions: a glare control mode with the blinds up, and a split mode with the blinds down over the top daylight harvesting section, used approximately the same amount of lighting as the reference window with the blinds down. In an environment where the blinds are used some of the time, these two modes would use more energy than the standard window.

On an annualized basis, the full daylight harvesting mode (condition A) appears to use over 20% less lighting energy than the blinds-down reference condition, and possibly 6% less energy than the blinds-up reference condition. However this mode did not provide the same level of visual quality or control of glare as the blinds down reference condition. This mode might be acceptable for a situation involving less window area, and better shading or orientation, but it is not likely to be acceptable for conditions as severe as seen in the testbed.

The split mode condition (condition E) manages to use about 13% less light energy (annualized) than the blinds-down reference condition, and has visual quality and glare indicators that are not significantly worse. It uses about the same lighting energy as the blinds-up reference condition, so it would still save some energy compared to a window where the blinds are used only some of the time. The situation is significantly improved when combinations of conditions are examined, as annualized savings ranged from 5 to 23% relative to the blinds down reference condition with very little loss in visual quality.

The testbed conditions were sufficiently severe that even the blinds-down reference mode appeared to not always be able to control glare to a satisfactory degree. Examination of glare versus time of day indicates this failure occurred when the windows were not being darkened, which means that control algorithm was the problem, and not the electrochromic windows themselves. These results need further study, and are good enough even as they stand to indicate a significant potential.

The presence of electrochromic windows does not guarantee energy savings or visual comfort and freedom from glare. However, the results from the testbed suggest that an electrochromic window system can be developed that can save some energy while maintaining visual comfort. The electrochromic system has the added advantage over a window blind system of being able to provide a view.

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Appendices

Weighted average glare calculation:

The glare indices, GI, were computed on a per-minute basis. It was assumed that difference between values 7 and below were not perceptible, so values less than 7 were set to 7. The data was then transformed to G' values where:

$G' = 10^{(GI/4)}$.

The weighted average glare index, $<GI_{weighted}>$ was computed by averaging the G' and transforming the average back to a glare index value:

$<GI_{weighted}> = 4 \times \log_{10}(\text{average } G')$.

The weighting makes larger glare index values more important in the average.

Probability of pulling blinds:

The odds ratio: no/yes = OR = $e^{(2.5517 - 0.001225 \text{ x window luminance})}$
The probability of the blinds being pulled is P(closed) = 1 - OR/(1 +OR)

Turbidity calculations:

Ideally, the illuminance turbidity, T_I, is calculated directly from a measure of the direct solar component. In the absence of a reliable measurement of this quantity, we made an estimate of T_I from the horizontal illuminance, E_H. The horizontal illuminance is the sum of the direct solar component, E_s, and the indirect sky luminance component, E_I. The solar component directly depends upon the turbidity through the standard scattering formula:

$E_s = E_0 \sin(Ø_s)\, e^{(-\text{alpha x } mT_I)}$,

where E_0 is the extraterrestial solar constant (≈ 123.2 klux), $Ø_s$ is the solar altitude, alpha is the Rayleigh scattering coefficient for light, and m is the relative air mass (m = 1 for $Ø_s$ = 90°). The air mass was computed from Mathokin's equation:

$m =[-\sin(Ø_s) + \{\sin^2(Ø_s) - 1 + (1.001572)^2)^{1/2}]/ 0.001572$.

The Rayleigh scattering coefficient depends upon air mass, because some wavelengths are scattered out of the direct beam more efficiently than others, with the result that spectral composition of the beam changes as it goes through more air. An approximate fit for the change in alpha for light is:

$\text{alpha} = (10.313 + 0.5934\, m)^{-1}$.

The turbidity is essentially defined by the direct component. To calculate it from the horizontal illuminance it is necessary to estimate the indirect component as a function of turbidity and solar altitude. Values for the indirect component contribution to horizontal illuminance were taken from the IESNA handbook (1984). The following equation fit 99.7% of the variance:

$$E_I = E_0 \sin(Ø_s) [0.7842\text{alpha x } mT_I (1 + 0.5934(\sin(Ø_s)-1))\, e^{(-\text{alpha x } mT_I)} + (1 - (1 + \text{alpha x } mT_I)e^{(-\text{alpha x } mT_I)}/(0.0694T_I +1.8012)].$$

The illuminance turbidity was found from an iterative back solution to the horizontal illuminance. A truncated geometric mean was used to compute a summary value for the turbidities for the day. Values were truncated to the range of 1.5 to 60.