Developing Predictive Venetian Blinds Control Models using Visual Comfort Predictors

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ABSTRACT: The goal of this study was to develop predictive window blind control models that could be used as a function in energy simulation programs and provide the basis for the development of future automated fenestration systems. Toward this goal, a window blind usage survey and a field study were conducted in Berkeley, California.

Results from the survey (n=113) showed that window blinds were closed for multiple reasons, among which the reduction of daylight glare was the primary closing reason. Thermal comfort and visual privacy were specified as subsidiary reasons. For the field study, measurements of luminous environmental conditions were cross-linked to the participants' assessment of visual comfort sensation and the Venetian blinds closing preferences (n=83). Four physical environmental predictors, including the maximum window luminance, the background luminance, the average window luminance, and the vertical solar radiation were found to correlate with the reported visual comfort sensation. Using the longitudinal regression techniques, four predictive window blind control logistic models were derived. As hypothesized, the probability of a window blind closing event increased as the magnitude of physical environmental factors increased ($p<.01$).

This study extends the knowledge of how and why building occupants control Venetian blinds in private offices. This study concludes that future work is needed to develop control algorithms that maintain satisfaction while allowing the energy-saving potential of automated shading systems to be fully realized.

Keywords: window blinds, visual comfort, occupants' control

1. INTRODUCTION

The fenestration system of a commercial building drives much of the building's energy consumption. When exterior shading is inadequate, building occupants must rely on interior shading devices such as venetian blinds and shades for controlling the amount of light and heat that enters their offices. Even though such devices can make conditions more comfortable for building occupants, previous research has shown that venetian blinds are adjusted infrequently [1, 2], and that blinds and shades are usually set for worst-case conditions [3].

When used correctly, however, shading devices can greatly reduce the amount of direct sunlight admitted into a space, substitute electric light with daylight, and thus reduce energy consumption. In order to harvest such energy-saving benefits, many fenestration systems with automated components integrated with daylight dimming systems have been developed.

While significant energy savings and peak demand reductions are possible through automatically controlled blinds [4, 5], many buildings that have automated shading systems are reported to experience serious technical and operational problems [6-9]. Many of the problems appear to come from misjudgments at the design stage of how building occupants interact with the shading systems. Occupants often dislike the systems and find ways to override, circumvent, and disable them. If designers better understood what occupants require or desire from the fenestration systems in their offices, then it would be possible to design better control strategies for automated systems.

Currently, there are numerous studies that investigate window blinds and shades usage [1, 2, 10-15]. However, there are only two simple window blind control models [14, 15]. The literature review has identified two major gaps in the field. First, the existing window blind control models are oversimplified. The blind control models are constructed with an all-or-none absolute threshold rule. Window blind control should be expressed in terms of probability of blind movement in correlation with visual or thermal factors. Secondly, previous studies of window blind control were not conclusive; not all major façade orientations were monitored in a single study.

This research examines building occupants' behavior when controlling window blinds in air-conditioned office buildings and derives predictive control models by observing how occupants interact with a manual system over which they have varying degrees of personal control.

2. OBJECTIVE

The objective of this research project is to develop predictive manual control models for window blinds that can be used as a function in energy usage simulation programs, and to provide the basis for the development of future automated shading systems that respond to the users' satisfaction and preferences.

The main hypothesis is that the probability of window blind closing events is a function of physical environmental conditions that are related to the occupants' perception of indoor comfort with the emphasis on the visual comfort predictors.

3. METHOD

Toward the research objective, a two-part study, the window blind usage survey and field study, of window blind control behavior was conducted in Berkeley, California during September 2004 to February 2005.

3.1 Research Participants

Research participants were recruited from various institutions, private companies, and professional organizations to participate in the survey portion of the study. Those who participated in the survey were invited to participate in the field study.

This research reports survey results from a total of 187 respondents from the different organizations in Berkeley, California, in which 113 respondents met the preliminary participant selection criteria. Because the recruitment and solicitation were initiated through email, response rate could not be verified.

For the field study, approximately 52% (60 people) of the qualified respondents expressed willingness to participate in the field study. Results were obtained from a total of 25 building occupants.

3.2 Study Variables

The dependent variable is the occupants' window blind closing preference (yes, want to close = 1, no change = 0). Variables that are a part of an equation used to calculate visual comfort or cited in previous window blind research were considered as independent variables.

A few secondary factors (satisfaction with view, need for privacy, age, and gender) were included in the survey portion of the study, but were not taken into consideration in the field study portion due to a limited number of research participants.

3.2.1 Visual Comfort Variables

There are many predictive models of visual discomfort. These models all share similar predictive equations which include luminance of the source (L_s), adaptation (or background) luminance (L_b), position of the source relative to the line of sight (p), and apparent size of the glare source (ω) [16]. All of these models can be expressed using the same general form:

$$G = \frac{L_s^a \cdot \omega_s^b}{L_b^c \cdot p^d} \quad (1)$$

For daylit condition, the Daylight Glare Index (DGI) is the only model that has been widely accepted in predicting discomfort glare from large sources such as windows. This research monitors several components of the basic glare formula:

L_{win} Average luminance of the window (cd/m^2)

L_{glo} Background luminance (or luminance measured at the eye) defines as the average luminance of the interior room surfaces (including window) and calculated as luminance averaged over the hemisphere of view (cd/m^2)

L_{mxwin} Maximum luminance within the window area (cd/m^2).

Luminance data were gathered and processed with the High Dynamic Range (HDR) imaging program called Photolux. The HDR images were captured at the seated location of each research participant, looking toward window wall at 1.22 m (4 ft) from the floor (see Figure 1). Calibration detail of this method can be found in [17]

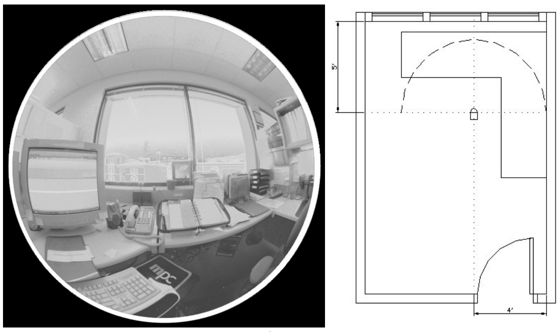

Figure 1: Example of an equidistant projection luminance map captured at the seated location of each research participant (left) and the typical digital camera viewpoint, looking directly at window (right).

The protocol of the field study was designed based on the window blind usage survey results. The survey data showed that typical building occupants usually kept their window blinds at fixed positions (mostly closed) and rarely adjusted them during the day. Because the driving factors for closing window blinds are not present when window blinds are closed, the field study protocol included opening the window blinds at occupants' workspaces to the fully opened position at the beginning of the test. After a brief period of adaptation to the raised blinds (5-10 minutes), research participants were asked if they wanted to close the window blinds, and if they did, they were asked for their reasons for closing the blinds.

Each participant was surveyed 1 to 4 times at approximately every two hours during normal work hours. This research design allowed a comparison between physical environmental condition and window blind closing preference, thus enabling the investigator to derive probability models of window blind control.

3.2.2 Transmitted Vertical Solar Radiation at Window

Previous research suggests that vertical solar radiation at the window (*SOL*) should be used as a predictor for window blind closing events [14, 15]. In this research, the vertical solar radiation was measured at approximately 1.22m (4 ft) from the floor, and the solar radiation sensor was mounted to the interior face of the window glass.

3.3 Data Analysis

With a limited number of participants, data were repeatedly collected over a period of time. An applied longitudinal data analysis technique, the Generalized Estimating Equations (GEE), which takes into account within-subject covariates, was chosen as the main data analysis technique.

The data were analyzed to derive logistic models that represent how window blinds were controlled as a function of physical environmental conditions. The results define various control models that are suitable for use as a window blinds control function in energy simulation programs and in actual automated blinds systems.

4. RESULTS

4.1 Window blind usage survey

4.1.1 Descriptive information

The survey sample included 50 male and 63 female responses (44.2% and 55.8% respectively) from all cardinal façade orientations. Approximately 42% of the survey participants were under 40 years of age. The majority of survey participants faced a sidewall (44.2%), whereas one-fourth of the sample placed their computer against a window wall. The survey showed that approximately 10% of the participants occupied an office on the north façade, whereas 24% occupied an office on the south façade. Approximately 32% of the participants occupied an office on the east or west façade. Finally, almost 60% of the participants reported that they did not have effective external shading devices, and the majority of the participants (almost 70%) had an office with an air-conditioning system.

4.1.2 Window Blind Closing Reasons

Data from Figure 3 show that window blinds were primarily used to control brightness and glare in the workspace. The control of heat and glare from the sun and visual privacy were secondary reasons for closing window blinds. A small portion (3.5%) of survey participants gave other reasons for closing their blinds and were classified into the “Other” category in which they stated that the window blinds were used to control glare and heat.

Control of direct and reflected glare on the computer screen (hereafter referred to as the Visual Display Terminal [VDT]) was the most frequently mentioned reason for closing window blinds (65% of respondents). The sources of this glare included direct sunlight (88.9%), the window (48.5%), the wall or partition (27.3%), and the ceiling (9.7%). Only 12.4% of the participants chose visual privacy as their closing reason.

This finding confirms the hypothesis proposed in previous research that window blinds are used primarily to control direct sunlight and glare.

4.2 Window blind usage field study

4.2.1 Descriptive information

The field study data were collected from 11 male and 14 female participants (44% and 56%, respectively) from all cardinal façade orientations. The majority (68%) of the research participants were age 40 and above. The field study data were collected in two buildings in Berkeley, California: the University of California Health Center (Tang) and the Lawrence Berkeley National Laboratory Administrative Building (LBNL).

Most of the participants at Tang sat facing a side wall, whereas most of the LBNL participants sat facing a window and wall corner. Only 20% of the total participants sat with their back against a window. In this study, the seating orientation variable was categorized into two major groups: facing window and facing wall. All participants use computer to conduct their daily task, in which most of the video display terminals are Cathode Ray Tube (CRT) type (average luminance of the CRT was 120 cd/m^2)

4.2.2 Summary of Independent Variables.

Table 1: Descriptive Statistics for Independent Variables.

Var	Mean	SD	Min	Max
L_{glo}	578	558	126	2628
L_{win}	2002	1235	270	5761
L_{mxwin}	11100	7514	1067	34058
SOL	75	86	4	357

Table 1 presents descriptive statistics for each independent variable. The distributions of all of these variables were strongly skewed to the right. Therefore, a log-transformation was applied to each skewed variable prior to the derivation of logistic models.

4.2.3 Logistic window blind control models

The main hypothesis in this study was that window blind closing events could be predicted as a function of physical environmental conditions. To test this hypothesis and derive a window blind model, a longitudinal logistic regression was performed using physical environmental variables to predict window blind closing events.

The logistic regression coefficients for each predictor variable are summarized in Table 2. For the standard regression, Nagelkerke’s r^2, which is based on likelihood, is shown. The percentage of correct prediction, tallied from the model’s estimates, is also shown for comparison. For the GEE models, the regression coefficients, the Wald statistic, the within-subject correlation (XTcorr), and the Akaike Information Criterion (AIC) value for each independent variable are shown.

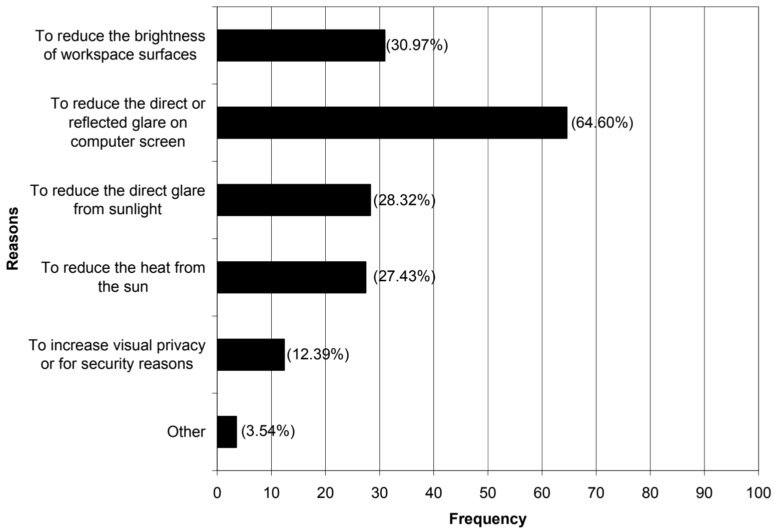

Figure 3: Window blind closing reasons.

Table 2: Summary of Logistic Regression Analysis for Variables Predicting Window Blind Closing Events

		Standard Regression						GEE		
	Variable	β, α	LR	r^2	% correct	AIC	ROC Area	β, α	Wald	XTcorr
L1	L_{mxwin}	4.93	30.47*	0.44	80.7	71.5	0.86	4.69	28.63*	0.16
	Constant	-17.95						-17.15		
L2	*SOL*	2.44	16.67*	0.29	72.6	73.0	0.78	2.59	22.65*	0.46
	Constant	-2.58						-2.89		
L3	L_{glo}	4.86	21.37*	0.33	78.3	80.6	0.80	4.95	15.79*	0.21
	Constant	-11.29						-11.58		
L4	L_{win}	4.37	21.15*	0.33	73.5	80.8	0.80	4.36	23.12*	0.19
	Constant	-12.75						-12.83		

*$p < .01$

The significance tests for each logistic regression model were based on the Wald statistic, which is defined as the square of the ratio between the regression coefficient and its standard error. This statistic follows a χ^2 distribution with one degree of freedom.

Support was found for the current study's main hypothesis that window blind closing events can be predicted as a function of physical environmental predictors. The results showed that window blind closing events increased as the luminance and vertical solar radiation levels increased.

The logistic regression curves from the standard regression method (dash line) and the GEE method (solid line) are shown in Figures 4 and 5.

Data from Table 2 also showed that the logistic regression coefficients between two regression methods were comparable for luminance related variables and only slightly different for vertical solar radiation variables. Therefore, the Nagelkerke's r^2 and the percentage of correct prediction were also used to compare the model's goodness-of-fit.

Using the AIC measure, the results from Table 2 show that the model with maximum window luminance (L_{mxwin}) as a predictor (Model L1) has the smallest AIC criterion measure (71.5).

Base on AIC, this model is considered to be the preferred single variable model for predicting window blind closing events. The model with the largest AIC criterion measure is Model L4 which use average window luminance (L_{win}) as a predictor (AIC = 80.8)

The model with maximum window luminance (L_{mxwin}) as a predictor (Model L1) also has the highest coefficient of determination (r^2 = 0.44) as well as the highest percentage of correct prediction (80.7%). The model with solar radiation (*SOL*) as a predictor (Model L2) has the lowest coefficient of determination (r^2 = 0.29) and the lowest percentage of correct prediction (72.6%).

The probability of window blind closing event could be estimated by applying the regression coefficient and constant from Table 2 to the following probability equation:

$$P(X) = \frac{e^{-(\alpha+\beta X)}}{1+e^{-(\alpha+\beta X)}} \tag{2}$$

where
- $P(X)$ Probability of window blind closing
- α, β estimated regression coefficients

Table 3 shows the threshold luminance or vertical solar radiation values at probability of 0.5. These threshold values could be directly applied in predictive window blind control algorithms and energy simulation programs.

Table 3: Estimated Threshold Values (at p = 0.5) for Various Physical Environmental Predictors

Variable (unit)	Threshold Value
Maximum window luminance (cd/m^2)	4466
Vertical solar radiation (W/m^2)	13
Background luminance (cd/m^2)	225
Average window luminance (cd/m^2)	890

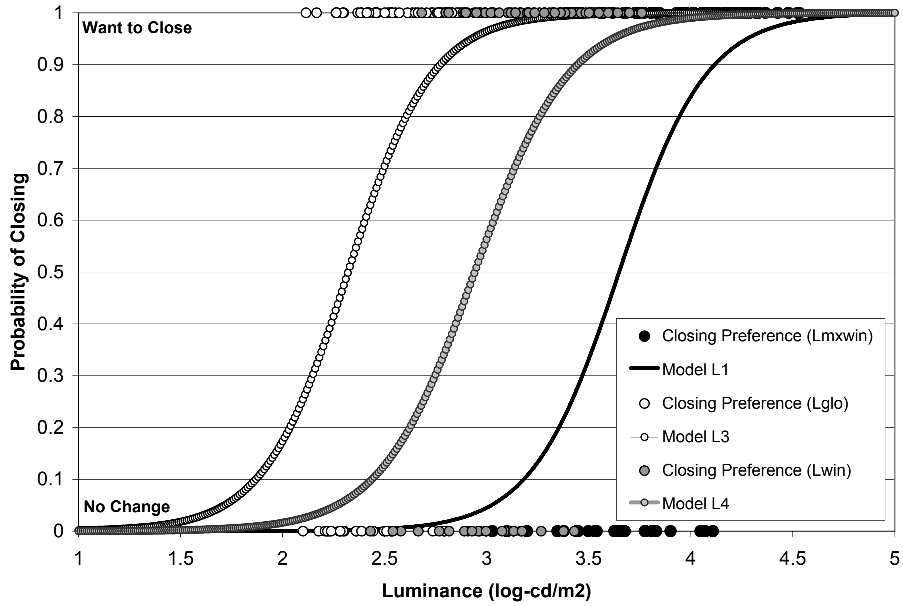

Figure 4: Model L1, L3 and L4; logistic models of window blind closing events as a function of maximum window luminance (L_{mxwin}), background luminance (L_{glo}), and average window luminance (L_{win}) respectively.

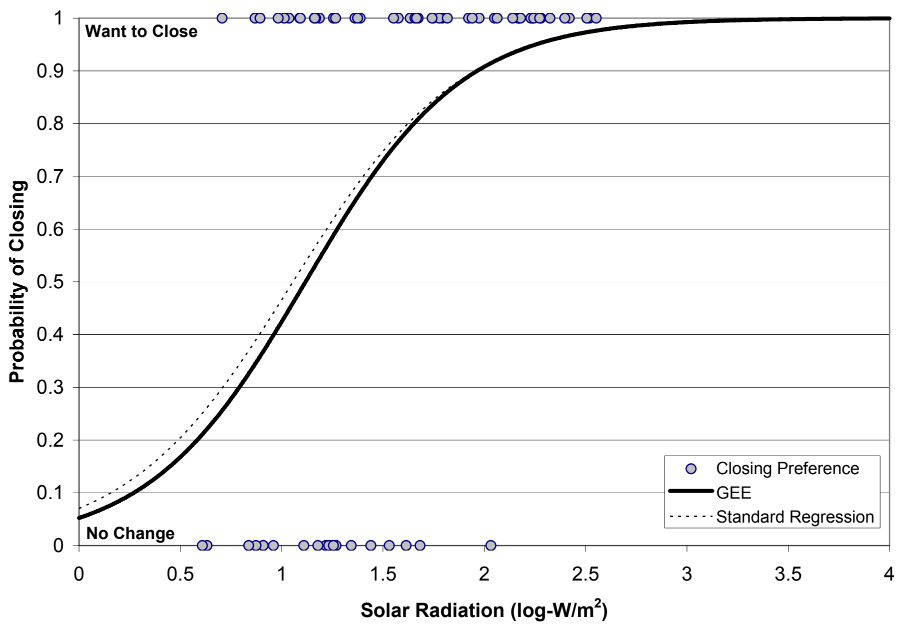

Figure 5: Model L2, logistic model of window blind closing events as a function of vertical solar radiation at the window (SOL; expressed in log scale).

5. CONCLUSION

This paper has presents results which enable the probability that occupants of the air-conditioned offices will close their window blinds as a function of visual comfort predictors.

Data from the window blind usage survey and field study were collected from participants who occupied offices with Venetian blinds in Berkeley, California between September 2004 and February 2005. These data supported the research hypothesis that the probability of a window blind closing event is a function of physical environmental conditions.

In this research, many predictive window blind control models were derived as a function of interior luminance characteristics and transmitted vertical solar radiation. In these models, the probability of window blind closing event was found to increase as the magnitude of visual discomfort predictors.

It is expected that these results can be easily applied to the computer simulation programs such as DOE-2 and EnergyPlus as well as in an actual automated window blinds systems in which the users can control the schedule of the window blinds as a threshold control (shades close depending on the condition set during the simulation) or probabilistic control (as a probability function).

The results reported are limited to a specific group of participant in particular climatic and contextual conditions. There are many factors that could potentially influence visual comfort perception and window blind control behaviour such as shade type, thermal discomfort, personal preferences and most importantly, task type and task luminance. For example, a separate study [18], which used Liquid Crystal Display (LCD) instead of CRT, reported higher average window luminance threshold value than the threshold value in this study. Therefore, it was hypothesized that task type and task luminance may influence how building occupants control window blinds. It is suggested that future studies should address this issue in detail.

This study concludes that future work is needed to develop control algorithms that maintain satisfaction while allowing the energy-saving potential of automated shading systems to be fully realized.

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