Time Lapse Simulation of Office Environments for Human Appraisal of Photovoltaic Glazed Windows

KEITH E. SYLVESTER
LOUIS G. TASSINARY
Texas A&M University

INTRODUCTION

In the design and use of photovoltaic glazed windows in commercial buildings, there are many questions asked by the building community. Although many of their concerns are quantitative, qualitative issues continually arise. The National Renewable Energy Laboratory (NREL) has stated that the greatest environmental concern surrounding building integrated photovoltaic systems is how they aesthetically affect people (DOE, 1993). The following section discusses this condition and searches for a causal relationship between window transmittance and human satisfaction.

PEOPLE AND WINDOWS

As indicated by the prior research (Biner & Butler, 1989), people desire windows in their indoor spaces. In the studies by Cuttle (1983), Collins (1975), Keighly (1973), Markus (1967), Wells (1965) and Wotton (1983), (as cited in Biner & Butler, 1989), it was demonstrated that people prefer the visual presence of daylight or sunshine to artificial light in offices. The studies showed that there was a positive relationship between the size of the window and people's preference for them. That is, larger windows that allowed more daylight and sunshine into spaces are generally preferred over smaller ones that do not.

However, other researchers have found that subjective responses to window preference are more influenced by the past standards in building construction than the personal preferences of people (Biner and Butler, 1989). Biner and Butler also found that window preferences and factors vary more widely than prior research has indicated. Hence, the effect of reduced light transmission and visibility of a photovoltaic glazed window on human preference is uncertain. Nonetheless, based on Cuttle's study it appears that there is a positive linear relationship between transparency (visibility) of the PV window and aesthetic preferences. Accordingly, the study attempts to validate that photovoltaic windows will produce a view that is acceptable to human subjects when compared to a similar view using clear glass.

ASSESSMENT MEASURES

Past studies, aimed at providing a description of affective quality attributes to environments, indicate that three dimensions—arousal, pleasure, and dominance—are required to assess the affective attributes that an individual assigns to a place. Measurement of these three dimensions was suggested by the semantic differential evidence of Osgood (as cited in Russell and Pratt, 1980). In addition, other multidimensional scaling studies of the influencing parameters indicated that, besides dominance, there are a number of secondary dimensions beyond arousal and pleasure that are cognitive in nature. However, when denoting the emotional state of people, it is the view of Russell and Pratt (1980) that only two orthogonal and bipolar dimensions—pleasure and arousal—are required. On these grounds, Russell and Pratt developed the affect grid to assess pleasure and arousal simultaneously as independent dimensions, where pleasure is the bipolar opposite of displeasure and arousal is the bipolar opposite of sleepiness.

Assessment of reliability of the Affect Grid was obtained through a comparative analysis of scales within four experiments: a) group ratings of emotion-related words, b) group ratings of facial expressions of emotion, c) individual ratings of facial expressions, and d) mood (Russell and Pratt, 1980). Scales compared in their study were: a) direct circular scaling, b) multi-dimensional scaling, c) uni-dimensional scaling, d) semantic differential scales of pleasure and arousal (Hehrabian and Russell, 1974), and e) Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988). Because the Affect Grid shows strong evidence of convergent validity with other measures of pleasure and arousal, it was used in this study to assess the emotional effects of photovoltaic glazing on office workers within a typical office space.

OPTICAL PROPERTIES OF WINDOW GLAZING

To offset high-energy consumption in commercial buildings, Low-E coatings have been proven effective in reducing energy use. In cold climate regions, these coatings block or reradiate the infrared heat back into the space to reduce heat loss. In hot climate regions, by reversing the location of the solar control coating, infrared heat is reflected to the outside to reduce heat gain (Johnson, 1991).

In 1989, a U-value determination method was adopted by all glass manufactures in the United States. This method was based on the U.S. Department of Energy's "WINDOW 3.1" computer program for predicting U-values based on the center of the insulating glass units. While measurement of the optical properties of advanced glazing have been established (Rosenfeld, 1998), NREL has developed a measurement guide for photovoltaic performance testing (Myers, 1997). Using spectral radiometric instrumentation, broadband optical radiation, otherwise referred to as the broadband wavelength within the total spectrum, is separated into spectral components to understand the spectral dependence of PV device.

Nonetheless, the measured data for optical properties of advance glazing are necessary inputs to computer simulation programs used to determine the energy performance of the glazed system and their effects on the building's energy use. These data also determine quantitative measurements for the assessment of the quality of the transmitted light and its spatial distribution. Such quantitative assessments are necessary for the successful introduction of advanced glazing concepts by architects, designers and the construction industry (Rosenfeld, 1998). In this study, transmittance calculations for semi-transparent PV glazing (Nishikawa, 1994) were used to calculate a 40% transmittance of the windows (Sylvester, 2000).

MEASUREMENT

When presenting simulated environments to a group of subjects, a valid appraisal relies on how we display the environment (Danford & Williams, 1975). Presentation methods include: a) use of the real environment, b) scale models, c) slides, d) photographs, and e) video recording of a real environment. Due to time, cost, efficiency, and ease of analysis, studies of human responses to environmental stimuli by Danford and Williams used simulations such as scale models rather than the actual environment. It was found that the reproduction of important environmental properties and the selection of a reliable means of simulating those properties elicited responses that have some degree of agreement with responses elicited by the actual environment (Bechtel et al., 1987). Therefore, in this study, to convey an impression of the office environment with and without the PV glazing, videotape of computer simulated office environments was used.

State-of-the-art software that visually simulate virtual environments include Radiance (Ward, 1994), Lightscape (Lightscape Technologies, Inc., 1997) and RadioRay (Autodesk, 1998), all of which use radiosity algorithms to define numerically accurate renderings. When using such programs, the environment is modeled as three-dimensional geometric descriptions of building materials and include the attributes of reflectance, color, specularity (shininess), and opacity.

Unfortunately, when using radiosity software, an enormous amount of time is required for the setup and rendering of animated segments. Designed to allow the simple animated movement of cameras, radiosity systems do not determine the irradiance levels for specific sites, nor do they determine the reduction in solar irradiance due to the time of day. Such complex lighting calculations make it inefficient to use radiosity algorithms to simulate changing lighting variables. As a result, instead of using radiosity algorithms to simulate the lighting within the office space, a modified lighting approach was developed.

In this study, 3D Studio Max (Autodesk, Inc, 1996), a popular visual simulation software, was chosen because it allows the expedient and animated control of variables such as solar irradiance and the solar position of the sun. To obtain numerically accurate images with reference to lighting, the solar irradiance was calculated using PV F-Chart software and modified for input into the 3D Studio Max software. This method is discussed further in the Methodology section.

SOCIETAL IMPACTS

Despite the known benefits of photovoltaic systems, architects, builders and developers are still reluctant to use photovoltaic systems as integral building elements (Goethe, 1994). Their reluctance is due, in part, to a lack of understanding about the aesthetic aspects of BIPV systems. Therefore, to address their aesthetic concerns, we must define the environmental benefits of photovoltaic building products for the public and building community. In addition, we must understand what factors, such as aesthetics, will influence their acceptance (Kiss and Kinkead, 1996).

Finally, if society continues to demand architects to design in climates where ambient conditions are inhospitable, reducing energy consumption becomes paramount due to the continuous need for mechanical cooling and heating. Furthermore, if architects continue to seek new forms of architecture that are independent of the climate and orientation, renewable energy conservation methods must be utilized to provide as much renewable energy that is financially viable to operate such buildings. Thus, to improve the building's sustainability, a psychological analysis of photovoltaic glazing in commercial buildings will lead to a better understanding of their potential social acceptance.

METHODOLOGY

This study targeted high-rise buildings within densely populated urban centers in the United States. Within each census region (Northeast, Midwest, South, West) a typical city was selected. To insure that the selected sites had the appropriate characteristics of a downtown district within large urban centers, each selected city had a human population greater than one million, based on 1992 US Census Data.

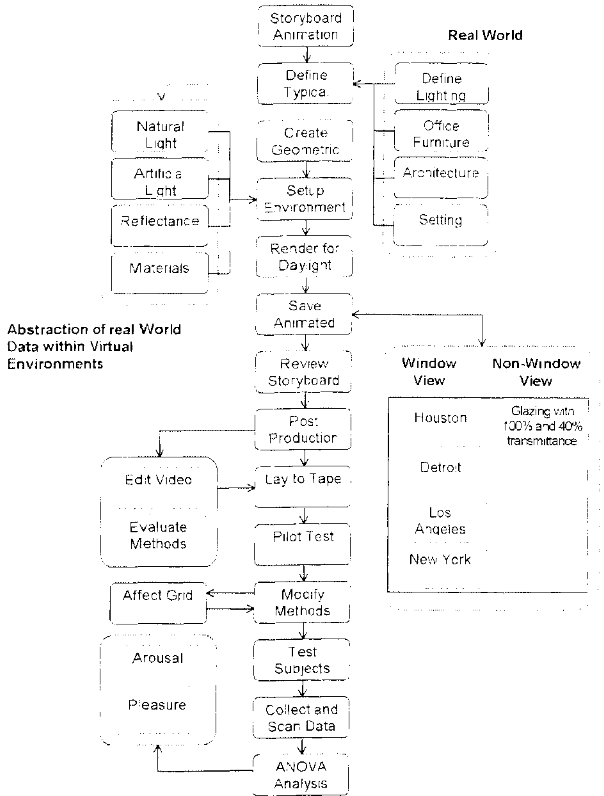

Fig. 1. Human Assessment Method.

Furthermore, in census regions where more than one city met the selection criterion, the city with the largest population was chosen. The cities selected for this study were New York (Northeast), Detroit (Midwest), Houston (South) and Los Angeles (West).

Human Assessment

To understand interior psychological effects of the visible light transmittance of windows on office workers, this study used a controlled experiment to test 188 subjects at Texas A&M University. This section describes the experimental procedures that were used when testing the subjects and the response format used to solicit the subject's feelings (Fig. 1). The average age of the subjects used was approximately 20 years. In addition, the modification of the measurement instrument and its interpretation were required when using a large population. Due to issues that arise when using computers to simulate the real environment, the mode of analysis—computer simulation of the real environments—is discussed in relation to material and light properties.

Experimental Procedures

Following standard instructions, the participants viewed videotape of randomly ordered digital image sequences. The videotape was shown twice, and the students were only allowed to respond during the second viewing. For five seconds, the video displayed a preparatory segment and notification that the sequence was about to begin. Following this, a digital image sequence appeared as a time lapse representation of one day from sunrise to sunset. The initial screening lasted 15 seconds, the final screening lasted for 10 seconds and at the end of each sequence, the phrase "Please record your response" was displayed for 10 seconds. In total, sixteen sequences were shown.

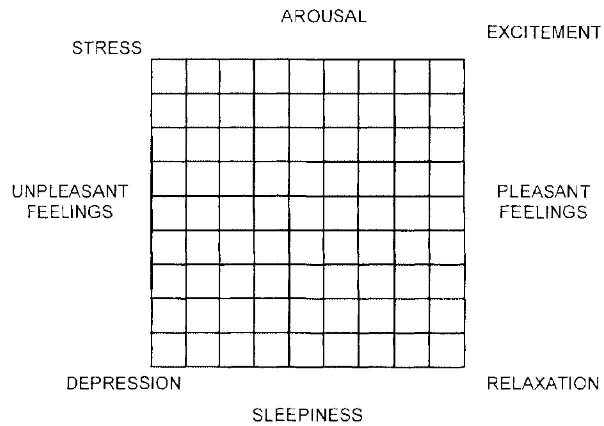

Fig. 2. Affect Grid.

Using the Affect Grid to measure arousal and pleasure as independent variables, the participants anonymously responded to the window stimuli by marking the appropriate square that expressed his or her feelings. The mean for each window treatment response was computed. These data were then averaged across subjects for all trials: 2 x 4 x 2 (transmittance/visibility x solar condition for each census region x transmittance levels - 100% and 40%). An analysis of variance (SAS Institute, Inc., 1993) was then used to test for significantly different treatment means.

Response Format

As shown in Fig. 2, the "Affect Grid" is a square grid abstraction of the "circular ordering of eight descriptors" (Russell & Pratt, 1980). The center of the square represents a neutral, average, everyday feeling. It is neither positive nor negative. In this study, the subjects used the grid to value arousal and pleasure as independent variables, one along each axis. The pleasure-displeasure score is taken as the number of the square checked, with squares numbered along the horizontal dimension, counting 1 to 9, starting at the left. The arousal—sleepiness score is taken as the number of the square checked, with squares numbered along the vertical dimension, counting 1 to 9, starting at the bottom.

THE SIMULATED ENVIRONMENT: TYPICAL OFFICE SPACE

The simulated office space has dimensions of 10 feet by 15 feet (Fig. 3). The floor plan contains two plants, one near

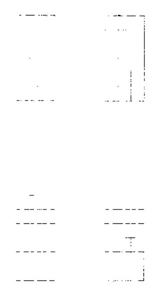

Fig. 3. Floor Plan and Reflected Ceiling Plan of a Typical Office Space.

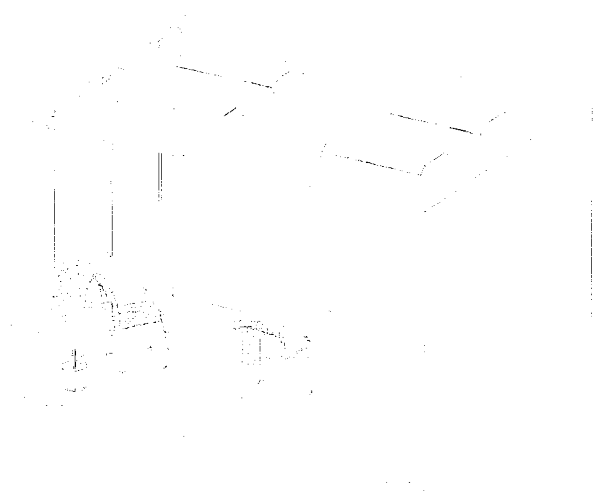

Fig. 4. Sectional View of Typical Office Space.

the door and one near the window, three chairs, one for occupant, and two for visitors, a desk, light fixtures, the camera position for window and non-window view, and a bookcase. The reflected ceiling plan shows the fluorescent fixture which contain three 32 watt lamps each, the sprinkler system, the 2' x 2' ceiling tile layout, and the supply air vent. The return air vents is a one-fourth inch gap on the peripheral of the light fixture. Major materials are the carpeted floor, painted metal door, eggshell painted walls with gray base molding, and textured ceiling tile with grill, and the glass material of the window. The major surfaces, the floor, the walls, the roof and the desktop, have been labeled to show their recommended reflectance (Fig. 4).

MODE OF SIMULATION

As mentioned earlier, 3D Studio Max (Autodesk 1996) was used to simulate the office environment. Due to the complexity of the material's properties and it's importance to the validity of the simulation, the next few paragraphs discuss the properties of the elements in the office environment and the lighting calibration. That is, how well does the simulation represent the real environment?

In the real world, the reflectance of a material is determined by its surface properties. However, the visual simulation software used in this study, as well as all other software, divides reflectance of a material into two components - shininess and reflection. For the purpose of this study the reflectance of surfaces maintain their relative values according to the IES Handbook (1981) and shininess factors were adjusted subjectively. As illustrated in Fig. 4., the recommended average reflectance of the painted walls and floor is 30%; the desktop is 30%; and the ceiling is 80%.

In the case of the lighting, the light fixtures were recessed and contained three T8 thirty-two watt fluorescent lamps, which translated into 96 watts (6720 lumens) per fixture. Because the lights are always on during the simulation, effects of the artificial lights were mainly checked for visual correctness. The selected day (June 21) was fixed for all selected sites, while the period of daylight hours, from sunrise to sunset, varied according to the selected sites. The hourly solar energy levels striking the windows were determined using time series plots generated with PV F-Chart software (F-Chart Software 1997) and the path of the sun for each selected site was determined using the internal programming of the software.

Specifically, solar energy levels were scaled in relation to the computers intensity levels for lights sources that range from zero (lowest) to 255 (highest). In this study, the solar energy levels falling on the windows were generated using PV F-Chart and scaled for all sites. All sites were grouped and the highest solar energy level was assigned to the highest software lighting level. All light was considered white in color. In addition, as a function of the visual simulation program, a multiplier of four increased the sun light levels to appropriately scale its intensity of the sun in relation to the artificial light sources.

The reflected light of the sun by the interior spaces was calculated by offsetting the scaled time series plots using an average surface. However, only one interaction of reflection was considered and was accomplished by creating an artificial light source that approximated the reflected sun and artificial light. Additionally, because this study reduces the window transmittance by 60% for the PV glazing, the calculated reflected light in the scaled time series plots was again adjusted to the decrease light entering the space for the PV window condition.

RESULTS

The participants in this study were males and females obtained from a university population - 16 participants were surveyed in the pilot test and 188 participants were surveyed in the final experiment. The study used a time lapse video representing one day to measure the arousal and pleasure

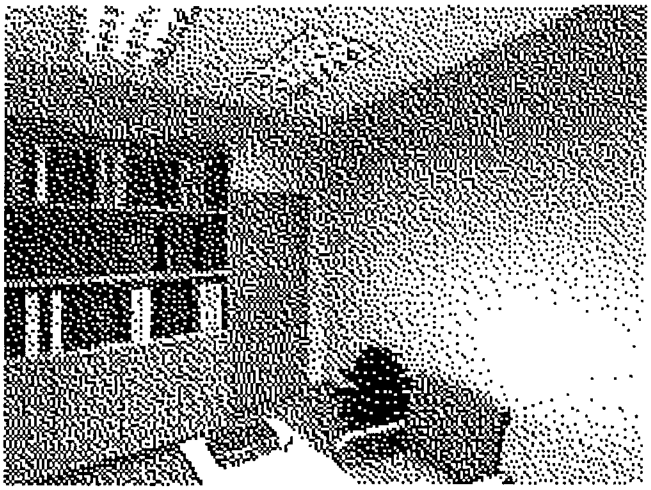

Fig. 5. Typical Non-Window View.

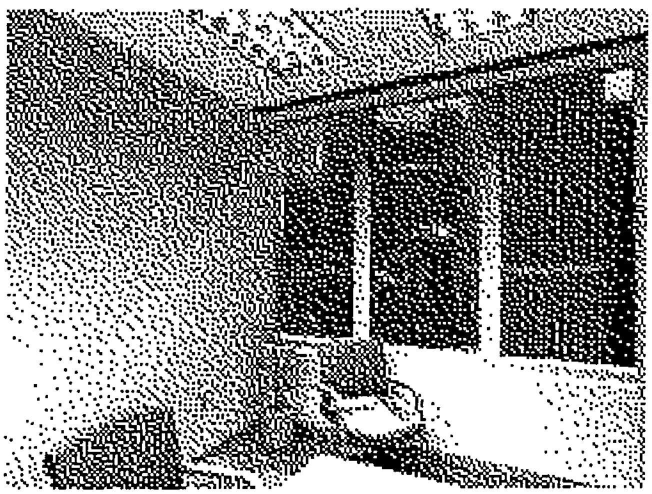

Fig. 6. Typical Window View.

effect for a window and non-window view in office spaces using PV windows. A 2 x 4 x 2 factorial analysis of variance analyzed the design. Overall, the study compared the light transmittance of PV glazing and view for the varying solar conditions of each site.

This condition was the same for all sites. In addition, the reflected lights of major horizontal surfaces within the scene (carpet, desk) were averaged. In the case of the artificial lights, the recessed fluorescent lamps in the space were always on and were therefore only checked for visual correctness. Once complete, the scene was rendered within the 3D Studio Max and recorded to videotape (Fig. 5 and Fig. 6).

ANALYSIS OF VARIANCE (ANOVA)

In all cases, the model for the analysis of the variance (ANOVA) was 2 (VIEW) by 2 (GLAZING) by 4 (LOCATION) within subject's design. To test the simulations for validity, this study surveyed the students for general comments about the study, in addition to the window assessment. In all, the responses of the students varied and often were related to the interior design of the space. Some commented that the space required more activity, some sound, desk items, and a few pictures on the wall. Others commented that direct light was preferred over indirect light and that the non-window view was boring or unpleasant because of the absence of direct light. A few responses categorized the changes as insignificant. It is important to note that the time lapse presentation was well received by most the students. In the next few paragraphs, the results of the window assessment are discussed.

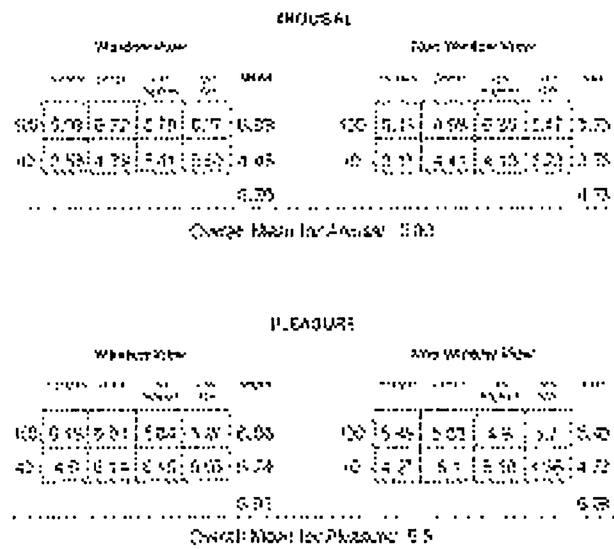

Fig. 7. Mean Responses for Arousal and Pleasure.

For the pleasure and arousal response, the overall mean results show that the subjects were only slightly aroused and pleased (Fig. 7). In both cases, the participants preferred a sitting position facing the window to the view facing the door. In addition, they preferred the spaces using the clear glass windows to the spaces using the windows with 40% transmittance. To interpret these data, a score of 5 represents a normal, everyday feeling (Russell & Pratt, 1980). A score higher that this indicates that the subjects felt more aroused or pleased and a lower score indicates that the subjects felt sleepier or unpleased. These measurements are based on a scale from 1 to 9.

In the ANOVA analysis of Arousal, the treatment means for VIEW and LOCATION are both significant, as well as 3 out of 4 interactions. That is, the variations in the test stimuli were being detected at various levels. In the case of the Pleasure, the treatment means for LOCATION and GLAZING are significantly different, as are 3 out of 4 interactions (Fig. 8). Overall, although people prefer clear windows to those with 40% transmittance, windows with 40% transmittance do not create significantly stressful or unpleasant feelings in people. Although there are significant differences in the mean responses for the varying window types, the subjects were only slightly aroused and pleased as indicated in the overall mean scores. Thus, the windows with a 40% transmittance are not perceived to create negative effects.

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Fig. 8. ANOVA for Arousal and Pleasure.

CONCLUSIONS

It is well known that people prefer daylight and windows in their environments. However, the primary function - to let in light - is overshadowed by economic factors associated with thermal properties of windows that may adversely affect human satisfaction of office workers. Consistent with this, architects must avoid presumptuous decisions that are based on market standards. By obtaining information on the current preferences of building occupants, architects expand their search of excellence by relating human acceptance to window or glazing types. More importantly, effects of windows on worker performance and preference, as indicated by this study, may be linearly related to the amount of light that they transmit, either due to the size or by transmittance of the window.

A "science-wise" architect avoids designing to minimum window standards by employing human assessment methods and basing his decision on external design factors that will influence the use and operation of the building. When considering photovoltaic windows, there is an inverse relationship between window performance and human satisfaction. Window performance is a function of the windows thermal properties and their effects on the building's energy budget, the electrical output of the photovoltaic glazed window, and the transparency of the window for a desire electrical output. In addition to this, potential users of PV glazing must now consider the electrical output of the window system. That is, with lower window transmittances of photovoltaic glazing, there is reduced daylight entering the space, possibly resulting in a lower level of human satisfaction. In contrast, there is an increase in electricity production available to meet the energy demands of the building and reduce operating costs.

ACKNOWLEDGEMENTS

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