A STUDY ON PERCEPTION OF DAYLIGHT SHADOWS AND VISUAL COMFORT IN LIBRARY READING AREAS

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ABSTRACT

The Illuminating Engineering Society (IES) recommends illuminance and uniformity targets (1), which are at times difficult to achieve, especially with daylight only. Assessing visual comfort in daylit environments such as libraries is important, particularly since libraries often have large daylit spaces. The term "daylight shadow" is defined as the shadow produced by daylight and objects as opposed to shadows produced by electric light and objects. Architects and artists widely acclaim that shadows are critical elements that affect the building occupants' emotions and that, consequently, they warrant more empirical research. This study examines the visual comfort related to daylight shadows. The methodology uses both quantitative and qualitative approaches. In the summer of 2012, librarian interviews, pre-tests, and post-test surveys were conducted in three Oregon libraries. Based on survey responses from 93 subjects, the data showed there was a tendency for people to feel more visually comfortable if they had positive perceptions of daylight shadows.

1. INTRODUCTION

Historically, lighting energy conservation became essential for sustainable design in recent decades (2). In the United States, 10% of building energy consumption in 2010 was attributed to electric lighting (3). Maximizing daylight utilization is one strategy used to reduce electric energy for lighting. However, the variability of daylight challenges occupants' visual comfort. A key challenge for designers is to balance the building occupants' expectations and desire for electric lighting with long-term operational costs and performance. Researchers have studied the various physical factors of daylight, such as illuminance, luminance, glare, and electric lighting flickers, as well as human factors such as aesthetic qualities of daylight and views as attributes of visual comfort. Since most visual comfort studies focus on daylight, shadows are very often overlooked (4).

1.1 Perception of Daylight Shadows in Architecture

A number of architects recognize shadows as elements that contribute to a building's aesthetic and feeling of space (5). Yutaka Izue asserts that shadow is enormously influential in achieving happiness and sorrow (6); Tadao Ando proposes that daylight and shadow add richness to space and trigger dynamic space qualities (7). Moreover, researchers have found that shadowed space creates a feeling of refuge and less illuminated environments provide a sense of security and privacy (8). Daylight shadows are a significant part of architectural design. The daylight shadows in the Louvre Pyramid designed by I. M. Pei in 1989 and in the Institut du Monde Arabe in Paris designed by architect Jean Nouvel in 1995 visually connect the openings' designs to building occupants. In the Three Shadows Photography Art Center, daylight shadows cast on exterior walls resemble the pattern of surrounding trees and enrich the building façade (9). Furthermore, shadow patterns in the Phillips Exeter Academy Library articulate the concept of enlightenment in reading and reduce damage from daylight to the books. Besides that, daylight and shadow convey holy feelings in some religious buildings. The sun-worshipping ancient Egyptians oriented the Abu Simbel Temple so that the first daylight beam would shine on the gods at the deepest end on October 22 and February 22 (10). In the Church of Light, Ando projects daylight and shadow through a cross-shaped opening. The contrasting illuminance resembles the power of God and the ignorance of human beings.

1.2 Psychological Impact from Daylight Shadows

Sensations within architecture are more important than meanings and values defined by architects (11). Shadow, which subtly alters human sensation, at all times is the source of the unknown and abstraction (12). The human neurological system analyzes light based on the lighting differences instead of lighting alone (13). Contrasting daylight and shadow can subconsciously change the perceptions and feelings of people in the space (12, 14). Illumination of a space affects the psychological performance of people, as evidenced in their temper, impulsivity, and behavior (15). It has been found that students are less stressed and more passionate about classroom programs when the lighting is lowered (16). However, low illumination stimulates a person's consciousness of others' nearness (17).

1.3 Visual Comfort

The perception of indoor visual comfort, which involves building occupants' satisfaction and space assessment, depends upon a complex evaluation system. Comfort assessment is primarily how people perceive a space. A previous study proposed that comfort evaluation is a structure consisting of "physical, physiological, psychological and social" attributes of building occupants (18). Fulfillment of comfort is found to relate to the expectations of people and how space satisfies building occupants' requirements. Aesthetic judgment is an attribute influencing people's perception of a space (19, 20). Researchers have also discovered that beautiful spaces improve concentration and productivity (21, 22). Building occupants in beautiful architectural spaces are sometimes more likely to tolerate uncomfortable lighting conditions in indoor environments. Since well-designed shadows essentially improve the aesthetics of spaces, perceptions of shadows tend to affect visual comfort.

1.4 Daylight Shadow in Library Design

At present, libraries are essential spaces for education and socialization. A library is a good building typology for this study, since library buildings consume 45% of building energy for maintaining electric lighting fixtures to achieve good visual conditions (23). More research on the presence of daylight shadow in library space is necessary to assist architects in achieving visual comfort and environmental goals. Visual comfort in libraries is closely connected to the occupants' attitude toward reading and studying. IES recommends a default illuminance ratio of 5:1 and 500 lux for users who are from 25 to 65 years old. Although IES encourages maximum utilization of daylight, it also recognizes that it is almost impossible to achieve lighting uniformity target with. However, people are often found to be comfortable outside the IES visual comfort zones. Visual comfort assessment requires further studies on human perceptions.

2. THE PROBLEM & HYPOTHESIS

This research seeks findings through addressing the following questions: What are people's opinions regarding patches of shadows and shadow movements in libraries? How are perceptions of shadow patches and shadow movements related to evaluation of visual comfort? Can shadow be designed consciously by architects to improve visual comfort in reading spaces? Therefore, the hypothesis of this paper is: library patrons are visually more comfortable in libraries with satisfying daylight shadows.

3. METHODOLOGY & EQUIPMENT

Three college libraries were selected as locations for this study. Daylit reading spaces with curtain walls or large windows were selected. Physical measurements of lighting and human subject evaluations were conducted to evaluate these reading spaces.

3.1 Pre-Test

The researcher conducted a pre-test to select the library areas with the most beautiful shadows. Photos of these spots were taken to capture images of shadows. Five photos were eventually selected from each library. A group of volunteer subjects with architectural and other backgrounds, participated in evaluation of the shadow images. Architecture students and faculty were considered to be subjects with architectural backgrounds. Subjects with other backgrounds were considered to be building users.

3.2 Site Study

Assessment of the physical lighting conditions of the indoor environments in selected libraries included measuring illuminance, analyzing the use of electrical lighting fixtures, and calculating contrast ratios to determine glare conditions. The study referenced IES lighting standards as the guidelines for visual comfort determination. The site study also recorded other indoor visual comfort attributes.

3.3 Library Manager and Librarian Interviews

Library managers and librarians participated in interviews to provide their opinions regarding daylight shadows and visual comfort in the reading spaces. Librarians and managers also gave background information about the libraries and architectural designs during interviews. They

were asked for general information such as operational hours, temperatures maintained in the libraries, and where library patrons liked to congregate in reading spaces. Moreover, librarians were able to offer anecdotal feedback from library patrons based on their previous experience.

3.4 Library Patron Survey

Library patrons were invited to participate in a survey by verbal request. Surveys were conducted only during sunny days, so that shadow patches would be visible. The surveys consisted of qualitative questions for assessing the overall comfort, visual comfort, aesthetic qualities, perceptions of shadow patches, and perceptions of shadow movements. For shadow evaluation, there were questions asking the participants to give their impressions of shadow patches as "unpleasant," "frustrating," "interesting," or "beautiful" (24). Other questions asked the participants to give their opinions of shadow movements by selecting "disturbing," "uncontrollable," "helps to keep track of time," and "helps to relate to nature" (8). A continuous five-point scale was used for qualitative questions. Questions about visual comfort were asked before the questions about shadows. Locations of the subjects were recorded and illuminance measured with the Mastech Light Meter LX1010BS. The number of overcast days in the winter precluded a reliable number of days to conduct this study, so the study took place in the summer months of 2012.

3.5 Data Analysis

For qualitative survey question, positive scores (+1, +2) were assigned for positive responses and negative scores (-1, -2) for negative responses (Table 1). The average evaluation scores were calculated for questions, which consist of sub-attributes such as aesthetic qualities. A slight difference scoring system was designed for shadow evaluations. Positive and negative opinions of shadows were assigned positive and negative values, respectively, depending on the connotations of the adjective (positive/negative).

TABLE 1: SCORING METHOD

	Very Unsatisfied/ Strongly Disagree	Unsatisfied/ Disagree	Neutral	Satisfied/ Agree	Very Satisfied/ Strongly Agree
Score	-2	-1	0	+1	+2

Table 2 shows an example of this scoring method for each library survey subject. For example, a subject disagreed that shadow patches were unpleasant, agreed that shadows were frustrating and interesting, and was neutral about shadow patches being beautiful. The subject also disagreed that shadow movements were disturbing, agreed that the movements were uncontrollable, felt neutral that movements help to keep track of time, and agreed that the shadow movements help one to relate to nature. The circled numbers correspond to the evaluation options selected by the subject. After calculation, this particular subject's overall daylight shadow evaluation score is 0.25, which is somewhat positive.

TABLE 2: SAMPLE SCORING SHEET FOR A SUBJECT'S OPINIONS ABOUT DAYLIGHT SHADOWS

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Selected Score
Do you find "patches" of daylight and shadows in this location?						
Score for "Unpleasant"	+2	+1	0	-1	-2	**+1**
Score for "Frustrating"	+2	+1	0	-1	-2	**-1**
Score for "Interesting"	-2	-1	0	+1	+2	**+1**
Score for "Beautiful"	-2	-1	0	-1	+2	**0**
Do you find the movements of shadows in the space						
Score for "Disturbing"	+2	+1	0	-1	-2	**+1**
Score for "Uncontrollable"	+2	+1	0	-1	-2	**-1**
Score for "Helps to keep track of time"	-2	-1	0	+1	+2	**0**
Score for "Helps to relate to nature"	-2	-1	0	+1	+2	**+1**
Total score	**+1-1+1+0+1-1+0+1 = 2**					
Overall shadow evaluation	**2 / 8 = 0.25**					

The visual comfort evaluation results were plotted against the shadow evaluation results in charts to determine the relationships between these perceptions. The visual comfort evaluation results were plotted against evaluation results of other well-studied attributes such as overall comfort and views and aesthetic qualities, to verify the relationships, too. The paper compared these relationships for shadow evaluation analysis.

This study also compared the illuminance levels measured at the spots against IES visual comfort criteria for library reading spaces. The study sought to determine the discrepancy between actual visual comfort and expected visual comfort based on IES design guideline.

4. FINDINGS

4.1 Site Visit

Three libraries were visited within one week during the summer of 2012. The photos for the pre-test were taken during these visits of each library. Each library's background, history, and general layout were also studied.

4.2 Library A

Library A was a four-story complex. The library was designed and constructed in 1937. The south, east, and west facades had large windows from the second floor to the fourth floor. The largest study area, which was added in 1950 on the south side of the library, was the space for this study. The study area had double-story volume. There was a lawn area outside the south façade. Grass, trees, and adjacent buildings were the main scenes for the study area. The materials of the windows in the study area were designed to provide good thermal insulation, reduce ultraviolet penetration, and lower glare. Patches of shadow covered the study area partially most of the time. Library A was visited at around 3pm on July 20, 2012.

4.3 Library B

Library B was a five-story building built in 1965. The building had a rectangular shape with a semi-circle recession on one side of the rectangle. Curtain walls were designed for the curve façade of the semi-circle. Sunshades extruded from the ceiling level of the first floor. Daylight shadows were observable along the edge of the curved curtain wall. There were curtains, which are operable by library patrons, along the curved window. There was a narrow corridor along the curtain wall where the study carrels were located. A daylight shadow was cast on top of all the tables on sunny days. Library B measurements took place around 3pm on July 29, 2012; photos were taken at the study tables from the second floor to the fourth floor.

4.4 Library C

Library C was constructed in 1961. The entire library space was one story below ground level. There was a square atrium at the center and multi-story buildings along the four sides of the atrium. The architect designed the curtain walls around the central atrium. Patches of shadows were cast on the area around the atrium. There was no shading device on the walls. Horizontal decorating bars were designed on the curtain walls. The materials of the bars cast colorful shadows. There were study tables right next to the curtain walls. Shadows were also cast on the study tables. Library C measurements were taken around 9am on July 20, 2012. Photos were taken in the study areas along the east and west sides of the atrium.

4.5 Pre-test

Photos of daylight shadows were taken in each library during the site visit. 5 photos of each library were selected for pre-test surveys. 38 students volunteered to participate in the pre-test to select the images with the most beautiful daylight shadow. Of the 38 volunteers, 11 had architecture backgrounds and 27 had other backgrounds. The votes of the two groups were compared to predict the judgments of architects and building occupants.

For Library A, 30.0% of subjects voted for Image 1. Image 1 of Library A had large double-story windows onto the landscape. Image 1 and Image 5, which received 27.5% of votes, were brighter compared to the other images. For Library B, 45% of subjects selected Image 3, which had more diverse shadow patterns and material variety. In both Image 1 and Image 3 of Library B, the shadows cast by window mullions created a rhythm on the floor. For Library C, Image 4 was selected by 40.0% of subjects. The patches of daylight and shadows in Image 4 of Library C had various shapes, and the bookshelves in the image generated a graphic rhythm.

TABLE 3: SUMMARY OF PRE-TEST RESULTS

	Library A	Library B	Library C
Image 1	30.0%	30.0%	15.0%
Image 2	12.5%	5.0%	15.0%
Image 3	20.0%	45.0%	17.5%
Image 4	10.0%	12.5%	40.0%
Image 5	27.5%	7.5%	12.5%

Fig. 1: Selected Shadow Images from Library A, B, and C.

4.6 Library Patrons Survey

32 patrons of Library A, 31 patrons of Library B, and 11 patrons of Library C participated in the library patron surveys. An additional 11 volunteers participated in surveys in Library C to obtain a more balanced evaluation.

4.6.1 Comfort Level of Library Patrons

From the survey results, most of the subjects in the three libraries were satisfied with the overall comfort of the study areas (1.08). High performance window in Library A and curtains in Library B may be the reasons for the better visual comfort evaluations (0.94). Subjects from Library C were slightly neutral about visual comfort (0.67). The results are consistent with the fact that patches of shadows directly covered all the study tables in Library C. Subjects from Library C were neutral about lighting for using computers (0.70). The strong lighting contrasts in study carrels and bookshelves in Library C may be the cause for lower satisfaction. The limitation of these questions is that most of the subjects were conducting only one or two of the activities listed when they did the survey. The evaluations of other activities were based on their previous experience or estimation.

4.6.2 Library Feature Evaluation

Table 4 shows the higher satisfaction with views in Library A and B (1.34 and 1.26), while subjects from Library C were somewhat satisfied (0.77). Views from Library A and B were wide open to the outdoor natural landscape. However, views from Library C included only a small, enclosed, manmade garden within the central atrium. The general satisfaction regarding views indicates that the views for libraries are usually well designed. Subjects from Library C were satisfied with or neutral about most of the qualities, except for the brightness of the space (0.67). The result corresponds to the fact that all the study carrels in Library C were right next to the curtain walls and the illuminance levels in Library C reading spaces were generally high when shadows appeared.

4.6.3 Visual Discomfort and Shading Device

The opinions regarding sources of visual discomfort were very diverse. This finding indicates that lighting conditions in different libraries were very dissimilar from one to the other. In general, brightness, light distribution, and glare were the main sources of visual discomfort (0.28, 0.32 and 0.45). Subjects from Library A were mostly neutral about discomfort sources and the need for shading devices. The high performance window in Library A might explain the low discomfort, even without the shading devices. Subjects from Library B and C agreed that there were lighting issues related to direct sunlight. Subjects from Library B generally agreed that blinds were needed, even when curtains existed. The lack of shading devices and performance strategies in Library C might explain the evaluations in Library C. Subjects from Library C tended to favor shading devices which did not block the views. Overall, subjects were slightly neutral about shading devices.

TABLE 4: SUMMARY OF SURVEY RESULTS

	Library A	Library B	Library C	Total
Score Calculated from Opinions				
Overall comfort	1.00	1.10	1.13	1.08
Visual comfort	0.94	0.94	0.67	0.85
Lighting conditions for activities				
Reading/writing	1.03	1.06	0.70	0.93
Using computer	0.90	0.90	0.07	0.63
Searching books	0.61	0.71	0.43	0.59
Views	1.34	1.26	0.77	1.13
Aesthetic qualities				
Brightness	0.88	0.94	0.67	0.83
Spaciousness	1.03	1.13	0.47	0.88
Cheerfulness	0.47	0.81	0.40	0.56
Colorfulness	0.25	0.23	0.37	0.28
Privacy	0.16	-0.03	0.33	0.15
Acoustics	0.56	0.26	0.33	0.39
Sources of visual discomfort				
Brightness	0.19	0.26	0.41	0.28
Light distribution	0.19	0.32	0.45	0.32
Glare	0.28	0.52	0.55	0.45
Electrical light flicker	0.16	0.52	-0.03	0.22
Reflections	0.28	0.00	-0.03	0.09
Shading devices needed				
Blinds	0.26	0.58	0.27	0.37
Louvers	0.13	-0.13	-0.07	-0.02
External sun shade	0.16	0.03	0.29	0.16
Daylight-reflecting shelf	-0.16	0.06	0.31	0.07
Attention to shadows	-0.47	0.10	-0.07	-0.15
Opinions of "patches" of daylight and shadows				
Unpleasant	-0.19	-0.65	-0.30	-0.38
Frustrating	-0.42	-0.71	-0.43	-0.52
Interesting	0.16	0.35	0.10	0.21
Beautiful	0.34	0.45	0.20	0.33
Attention to shadows' movements	-0.03	-0.10	0.07	-0.02
Opinions of the movements of shadows				
Disturbing	-0.44	-0.74	-0.55	-0.58
Uncontrollable	-0.03	-0.50	0.00	-0.18
Help to keep track of time	0.35	-0.26	0.10	0.07
Help to relate to nature	0.48	0.32	0.37	0.39

4.6.4 Shadow Evaluations

Library survey subjects were somewhat neutral about noticing the shadows (-0.15). This result is very similar to the librarian interview results. The shadows in the libraries were paid little attention by subjects. Subjects from Library B had slightly more positive opinions about shadow patches. The presence of shading devices in Library B likely improved the subjects' control over shadows and led to shadow appreciation. As a whole, all subjects were inclined to have slightly positive shadow evaluations.

The question regarding noticing the movements of shadows obtained results that were very similar to those for the question about noticing shadow patches. Subjects from the three libraries were mostly neutral about noticing movements of shadows (-0.02). The subjects from the three libraries had slightly different opinions regarding the attributes of "uncontrollable" and "help to keep track of time." The curtains in Library B again were likely to improve the subjects' perceived control over shadows. However, the curtains might also have undermined the connection between shadow movements and time. In general, the subjects from all three libraries had slightly positive evaluations of shadow movements. The results confirm that these libraries do not create ideal shadows.

TABLE 5: DEMOGRAPHICS OF LIBRARY PATRONS

	Library A	Library B	Library C	Total
	No. of Subjects			
Average time spent in this library per day				
A few minutes	3	1	6	10
One hour	3	3	10	16
A few hours	22	26	13	61
The whole day	3	2	1	6
Subject's current activity				
Reading/writing	25	22	23	70
Using computer	8	13	7	28
Searching bookshelves	1	0	3	4
Others	1	1	2	4
Subject's Age				
< 25	19	20	20	59
– 65	11	11	10	32
> 65	1	0	0	1
Study/working hours per day				
One hour	2	2	1	5
Two to five hours	12	16	11	39
Five to eight hours	11	8	13	32
> eight hours	6	6	5	17

5. ANALYSIS

As stated in the methodology section, the shadow attributes were analyzed separately to evaluate the overall perceptions of daylight shadows. Figures 2 and 3 present the distribution of shadow evaluation scores from all the survey subjects. There were more subjects with positive scores for shadow evaluations. Most subjects had a score around +0.4. Based on this result, subjects were considered generally to have slightly positive opinions on patches of shadows and movements of shadows.

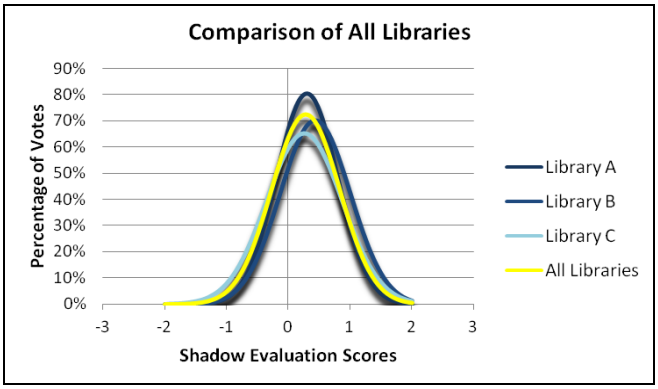

Fig. 2: Overall Shadow Evaluations.

Figure 3 shows the chart of visual comfort evaluations plotted against shadow evaluations and seeks a relationship between these factors. The sizes of the bubbles indicate the number of subjects who had the same selections. The gradient of the regression line is 0.3736, while the R^2 of the regression line is 0.0788, which is very small. There are insufficient data to indicate any correlation. However, a weak positive trend is found between these factors from the chart. There is a tendency for subjects who have more positive daylight shadow evaluations to feel more visually satisfied.

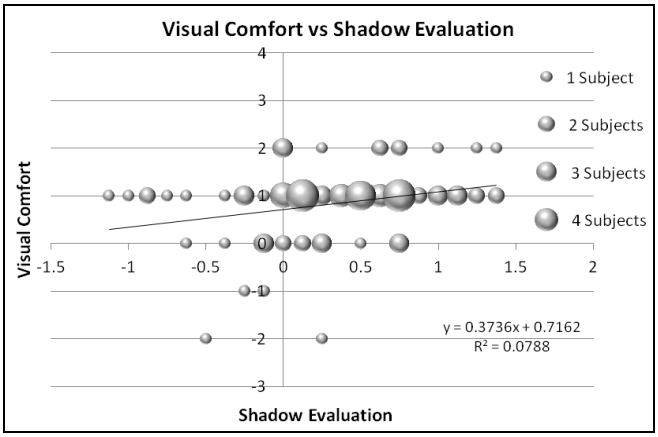

Fig. 3: Visual Comfort against Shadow Evaluation.

Similar analysis was done to study the relationship of visual comfort to well-studied attributes overall comfort, views, and aesthetic qualities. The evaluations of the aesthetic qualities combined the scores of the six qualities. The results indicate weak positive relationships between these attributes, too. The gradients of the regression lines of these charts are 0.63, 0.32, and 0.41, respectively. The R^2 values of regression lines are 0.25, 0.13, and 0.11, respectively. Therefore, there is no linear correlation, but a positive trend between visual comfort and these attributes. The results of the shadow evaluations are similar to those of view evaluations and can be used as a visual comfort attribute in further studies.

Figure 4 presents the lighting measurements from the libraries when the surveys were conducted. The green frame marks the IES' recommended lighting conditions for library reading areas. The blue bubbles represent the subjects in areas that met the IES standards for visual comfort, and the red bubbles represent the subjects in areas that failed to meet the IES visual comfort standards. The charts below shows that the majority of the subjects were studying under lighting conditions that put them within the IES visual comfort zone. A small number of subjects were in areas with conditions that put them far outside the IES visual comfort zone.

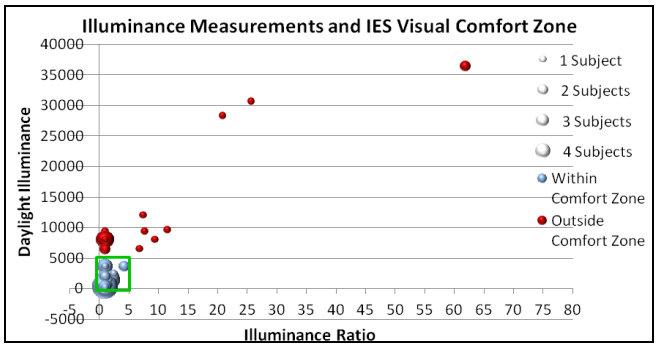

Fig. 4. Illuminance and the IES Comfort Zone.

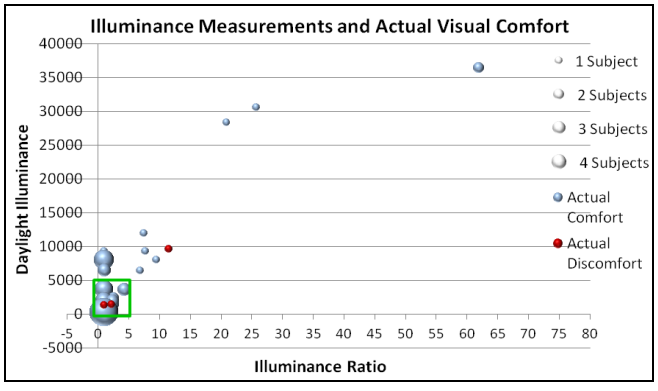

Fig. 5: Illuminance and Actual Visual Comfort.

Figure 5 shows the actual comfort of subjects in each condition. The blue bubbles represent the subjects who were satisfied with or neutral about their visual comfort; the red bubbles represent subjects who were unsatisfied with their visual comfort. The chart indicates that a number of subjects who were outside or far outside the IES comfort zone were satisfied with or neutral about their visual comfort in the space. There were also a small number of subjects who felt uncomfortable even in the IES visual comfort zone. It is found that 13 subjects who felt comfortable outside the comfort zone and 11 of them had positive shadow evaluations. 2 subjects who felt uncomfortable in the IES comfort zone and both of them had negative shadow evaluations. Although the sample size is small, the results are consistent with the positive trend between visual comfort and shadow evaluation.

The pre-test intended to analyze the votes of two subject groups based on their backgrounds. This test selected the most beautiful shadow images from each library and determined the disparities between perceptions of designers and users. The percentages of votes from the two groups were very similar for the Library A images. The percentages of votes from the two subject groups were somewhat different for the Library B and Library C images. However, the difference between these two groups was relatively small. The results indicate that aesthetic judgments of subjects with architectural backgrounds and other backgrounds are fairly similar; therefore, designers tend to design the daylight shadows that are appealing to building users.

6. CONCLUSIONS

The illuminance of some daylit reading areas of selected libraries did not fall within IES visual comfort zones during the summer of 2012. Very often the contrast between shadowed and daylit areas was higher than the recommended illuminance ratios. Nevertheless, subjects from three libraries generally expressed satisfaction with their visual comfort in daylit reading areas and also expressed positive opinions regarding shadow patches and shadow movements. There is a positive tendenc between visual comfort and daylight shadow evaluations. My hypothesis, "library patrons are visually comfortable in libraries with satisfying daylight shadows," is generally supported by the data in this study. However, since the sample sizes were small and the relationships are subtle, perhaps the nuances were not captured using the methods in this study.

A small number of survey subjects gave visual comfort evaluations, which contradicted the IES visual comfort standards. Subjects who were satisfied with conditions well

outside the IES visual comfort zone generally had positive opinions of daylight shadows, and subjects who were unsatisfied with conditions within the IES visual comfort zone had negative opinions of daylight shadows. Although the number of subjects was small, it is still feasible to infer that building occupants are more likely to tolerate undesirable conditions if they appreciate daylight shadows. Further studies are needed to sustain this argument.

According to the results of the pre-test, subjects had a distinguishable preference over daylight shadow images. This finding necessitates further studies on aesthetic evaluations of diverse shadow patches and shadow movements. With information from further studies, designers might be able to design shadow patches that are attractive to and visually comfortable for building occupants. Library manager and librarian interviews as well as patron surveys indicate that shadow patches and movements of shadows are not noticed by most occupants. Perception of daylight shadows tends to affect the subjects' feelings subconsciously.

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