Human Physiological Signal Based Building Environmental Controls for Visual Comfort

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ABSTRACT: People spend more than 90% of their time in buildings in the U.S. ("US Environmental Protection Agency | Report to Congress on Indoor Air Quality" 1989). This significant time length in a daily life naturally strengthens the importance of indoor environmental quality (IEQ), especially in an office environment, where the occupant's work productivity and health are highlighted. Among the IEQ components (thermal, air, lighting, acoustic, and spatial quality), the lighting environmental condition has the most significant effect on an occupant's visual comfort and sensations due to its instantaneous involvement into his/her environmental perceptions. However, depending on an individual's physiological characteristics, the preferred lighting conditions may vary and a single lighting setting will not be acceptable in all the cases due to various personal preferences. Therefore, this study is intended to identify a novel diagnostic method for developing a visual sensation model as a function of human physiological signals to provide an accurate estimation of individual visual perceptions. The purpose of this research is to investigate the potential use of human pupil sizes and their fluctuations to estimate a human subject's visual sensation for a diagnostic model to evaluate ambient lighting conditions that could detect any stressful condition, such as glare or high luminance, in an office workplace environment. This research included extensive human subject experiments, conducted in an environmental chamber, that collected human physiological signals (i.e, pupil sizes), while the ambient lighting conditions were being changed to coincide with a range of typical office building lighting conditions. For the experiments, a pupilometer was used and a visual comfort and sensation survey method was adopted, with 15 university students participating as the experimental human subjects. The research outcome showed the potential for using pupil sizes and their change rates as quantifiable input variables for diagnosing an individual's visual sensations.

KEYWORDS: physiological signal, human-building interaction, pupil size, visual comfort, visual sensation

1. BACKGROUND AND SIGNIFICANCE

People spend more than 90% of their time indoors in the U.S. (US Environmental Protection Agency 1989). For this reason, indoor environmental quality (IEQ) building components are extremely essential for maintaining the environmental health and work productivity of occupants in office workplace environments, as are their individual physiological conditions, which also have an impact. Recent studies have reported that 65% of building occupants are adversely affected by inappropriate lighting conditions in their workplaces, with glare problems, in particular, causing serious visual stress (Wilkins 2003). In spite of their significance, most office buildings have adopted guidelines that were empirically developed, primarily by the Illuminance Engineering Society of North America (IESNA) ("IES Guideline" 2010). Since those guidelines were developed mainly based on a conventional paper-based task work environment, their application could cause unnecessarily high lighting intensity in a computer-based task work environment, which is the most prevalent condition in today's workplace. In addition, depending on an individual's physiological conditions (age, pupil color, ethnic origin, personal cultural background, etc.), preferred lighting conditions vary considerably with different people. Their diversity in preferences may limit the successful adoption of current guidelines for application in various environmental and physiological conditions.

The human body has an autonomic function that regulates its physical responses to minimize any environmental stress, such as hot or cold temperatures or excessively bright conditions (Bitsios, Prettyman, and Szabadi 1996; C.-J. Choi et al. 2011; Taylor, Allsopp, and Parkes 1995; Noguchi and Sakaguchi 1999). For example, depending on the intensities of various stressors, the skin on a human body could sweat or control the surface body temperature to balance heat losses or gains caused by ambient thermal conditions, and pupil sizes could shrink or dilate in response to variations in light. Therefore, this research adopted human pupil sizes as a feasible physiological signal to estimate visual sensation conditions (based upon the principle of reverse engineering) that could illustrate subjective lighting sensations as a function of objectively measured physiological signals. The end result would be a novel method for visual quality assessment, such as a lighting simulation program and high-dynamic images, as compared with conventional methods that have primarily depended on pre-assumed human environmental reactions, instead of real human physiological responses.

2. METHODS

This research conducted extensive experiments using human subjects in an environmental chamber located in the School of Architecture at the University of Southern California. The chamber was equipped with multiple data collection devices and lighting and mechanical systems to generate a range of lighting and thermal settings that simulate real office work environmental conditions. The study also used a questionnaire survey to collect each subject's visual sensations and comfort levels in each revision of lighting condition. At the end of each revision, the subject was asked to report his or her visual sensation and comfort level on a 7-point scale answer sheet. It consisted of seven different options ranging from "dark (-3)" through "bright (+3), with a "neutral" condition (0) at the mid-point of the scale. The comfort level was also marked on a 7-point scale: "very dissatisfactory" (-3) through very satisfactory (+3) with neutral at the mid-point (0).

For collecting data on human pupil sizes, the experiment used a pupilometer (Model: ASL Mobile Eye XG), which is a wearable sensor similar to a ski goggle, that can measure a pupil size in pixels (Figure 1). The measurement was recorded at a frequency of 30Hz, and the collected pupil size data were transmitted to the database in a data acquisition computer through an interface developed using the LabView software with a sensing interval of 1 second. Through the interface, the test subjects reported their visual sensations and comfort levels by moving the 7-point scale bar button. Fifteen voluntary subjects participated in the test, and the data collected from 13 of the subjects were considered for use in the study analyses. The research was approved by the University Internal Review Board (IRB), and the demographic information about the study subjects is summarized in Table 1 below.

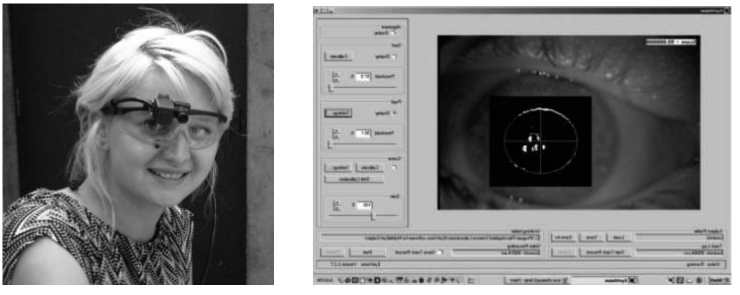


Figure 1. One of the PI's students wearing the pupilometer and the data collection software for pupil sizes

Table 1. Demographic information of the subject samples in the study

	Gender		Age		Eye color		Myopic	
	Male	Female	<25	>=25	Blue	Brown	Yes	No
Sample size	10	3	8	5	2	11	7	6
Percentage	77%	23%	62%	38%	15%	85%	54%	46%

The study selected illuminance and luminance as the lighting parameters to control in the chamber tests. The lighting setting was decided based upon a typical range of illuminance in the office environmental settings that were investigated in the PI's previous post-occupancy evaluation study of 29 office buildings within the U.S. (J.-H. Choi, Aziz, & Loftness, 2010 & 2009). The selected illuminance levels ranged from 50 lux up to 1500 lux, with 10-step changes that followed the order of lowest to highest, or vice versa to assure random variations in the experiments. The overall luminance was also estimated for each illuminance setting by using PhotoLux software, based on four pieces of fish-eye images that were captured with different aperture, and timing settings of a camera (Model: Nikon Coolpix 8400). For the lighting control, 14 units of 8 W-dimmable LED lamps were installed on the ceiling surface of the chamber, with each light bulb featuring 530 lumens (49 fc) in brightness and a color temperature of 2,700 K (4860 R). Only one subject was allowed to stay in the chamber for each test, with 5 minutes given for a visual acclimation in each lighting step change, and then data collection was made for 2 minutes. At the end of each step change, a visual comfort and sensation survey was reported by the subject, based on his/her visual perceptions about the lighting condition during the final 2 minutes, prior to the survey. Overall procedures followed in the study are summarized in Figure 2.

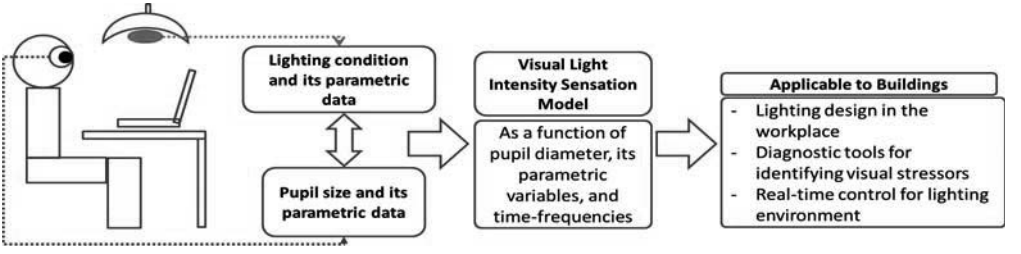


Figure 2. Procedures for data acquisition, and potential applications of the research findings (J.-H. Choi, Zhu, and Johnson 2013)

2.1. Illuminance and luminance settings in the chamber test

The illuminance level of the test chamber was controlled based on a 150-lux change step interval. The overall luminance was also estimated using PhotoLux software, as discussed in METHODS. As illustrated in Figure 3, there was a linear relationship between illuminance in the workstation and the overall luminance. The estimated correlation index was 0.99, with a statistical significance of p=0.000. Based on this linear regression formula (illustrated in Figure 3), all of the overall luminances in this study were estimated using the illuminance measured during this experiment.

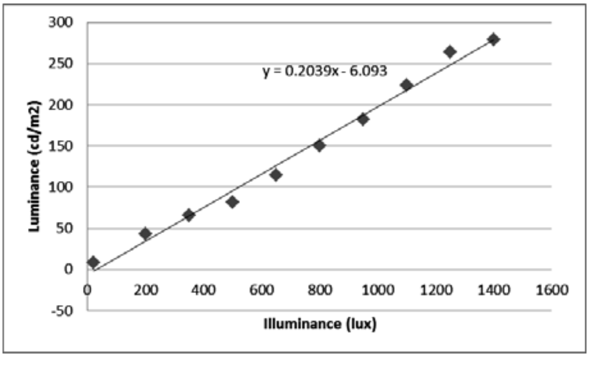


Figure 3. The correlations between illuminance and luminance of the experimental settings.

2.2. Pupil size data and its standardization per individual

The pupilometer adopted in this study uses the pixel as a metric for measurement. It detects the size of a pupil by the micro-camera facing the subject's eye while tracking the path of eye movement. As discussed in the authors' previous study (J.-H. Choi, Zhu, and Johnson 2013)), the raw data of individuals' pupil sizes are not comparable because pupil sizes and shapes vary in different individuals (Jones 1990). For this reason, normalized (i.e., standardized) data for each individual was used for data analysis using the formula introduced in the authors' previous study (J.-H. Choi, Zhu, and Johnson 2013) as follows:

$$Standardized\_Pupil\_size(\%) = \left(\frac{Pupil\_size(i) - Pupil\_size(neutral\_sensation)}{Pupil\_size(neutral\_sensation)} \right) \times 100$$

, where i is an eye's response to luminance intensity.

3. RESULTS AND DISCUSSION

Overall, subjects reported dark sensations on lower luminance, and brighter sensations on higher luminance. As shown in Figure 4, a confidence interval for each sensation of an individual clearly showed an increasing pattern, while the generated luminance was increasing. However, their perceived luminance levels were very different depending upon the individual. For example, Subject No. 1 reported a "neutral" sensation when the luminance was around 100 cd/m^2, while Subject No. 6 described a "neutral" sensation with a luminance lower than 50 cd/m^2.

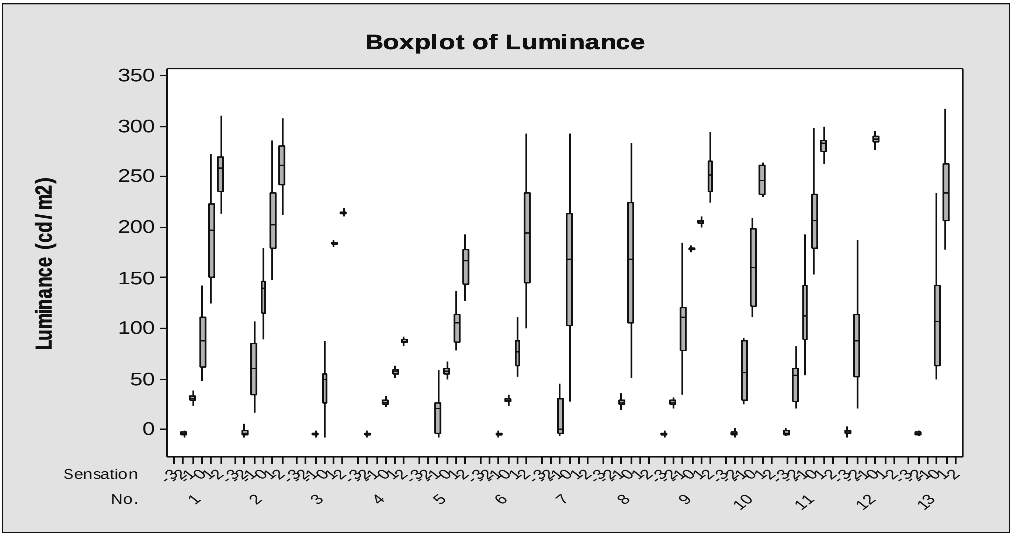


Figure 4. Luminance distribution in each subject's test and the 95 % confidence interval for an individual eye's response to luminance intensity ("No." indicates a subject ID).

Figure 5 illustrated the pupil size patterns for visual sensations based on the combined data of all individuals. Overall, the standardized pupil sizes decreased while the generated luminance intensity was increasing. The analysis of variance (ANOVA) test showed a statistically significant p-value that was lower than 0.05. This finding is clearly summarized in Figure 6. The chart contains basically the same data as Figure 6, but it shows a 95% confidence interval for pupil sizes per visual sensation. The interval lines are clearly differentiated from each other, and the length of an interval at neutral sensation is shortest, which indicates that the pupil size for a neutral sensation is more stable than for other sensations.

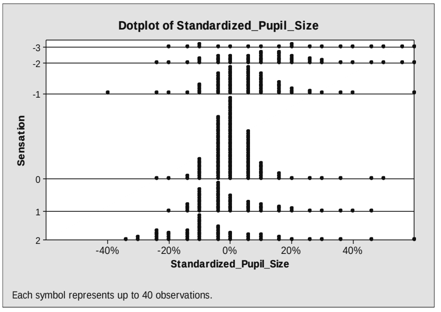


Figure 5. Overall standardized pupil size distribution per visual sensation to luminance intensity.

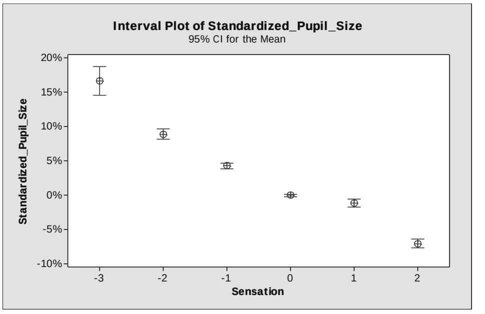


Figure 6. Interval plot of standardized pupil size per visual sensation to luminance intensity.

To check the consistency of pupil size changes per visual sensations for individuals, the study conducted comparison tests between subject groups of different physiological characteristics, (i.e., eye color, ethnicity, age, and myopic conditions. Since 13 subjects were selected for this study, the surveyed visual sensation data were grouped into "Dark" (i.e., visual sensation levels of -3, -2 and -1), "Neutral" (visual sensation level of 0), and "Bright" (visual sensation levels of +1, +2 and +3). As shown in Figure 7, the data were grouped by eye color. The distributions of pupil sizes were clear enough to differentiate the perceived visual sensations, and the ANOVA revealed that a p-value lower than 0.05 was statistically significant. The subjects were also grouped by age for a comparison test between age groups. The study used age 25 as a threshold to divide the 13 participants into two groups: younger than 25 (subject size: 8) and older than 25 (subject size: 5). Figure 8 illustrates a statistically significant difference between visual sensations in each group. Consistently, the pupil size differences were more than 5% in each age group between the Dark and Neutral sensations and between the Bright and Neutral sensations.

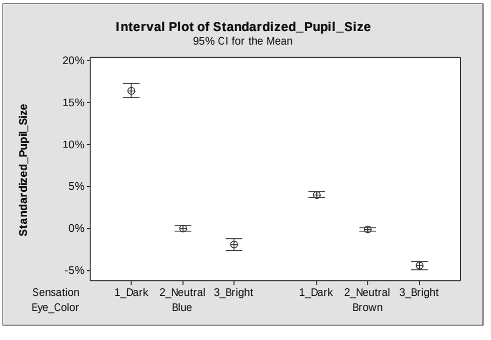


Figure 7. Comparison of overall standardized pupil size per visual sensation between eye color groups.

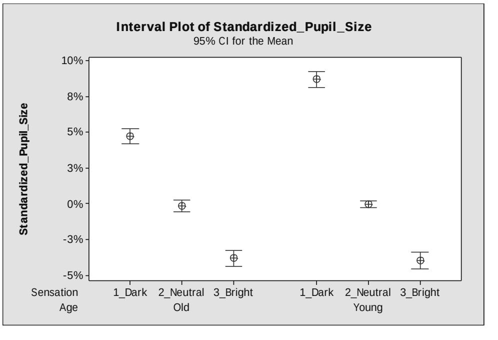
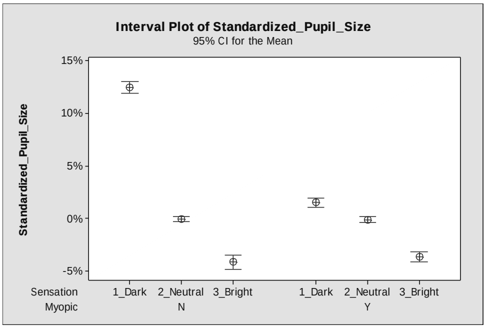


Figure 8. Comparison of overall standardized pupil size per visual sensation between age groups.

The study also compared the pupil size change patterns between myopic groups. In Figure 9, "Y" indicates the group who wore glasses, and "N" is those who had no glasses. The N group shows a significant difference in pupil sizes between the visual sensation levels, while the Y group shows only minimal differences. Even though the ANOVA tests of both groups show p-values lower than 0.05, that are statistically significant, the actual differences in pupil sizes between visual sensation levels in the Y group could be difficult to detect in reality. Figure 10 also summarizes the comparison between genders. The male group showed a statistically significant difference in pupil sizes, but the female group was not clear enough to show a difference in pupil sizes, especially between the Dark and Neutral sensation. The t-test of the pupil sizes between the Dark and Neutral sensations in the female group revealed a p-value of 0.632, which is not statistically significant.



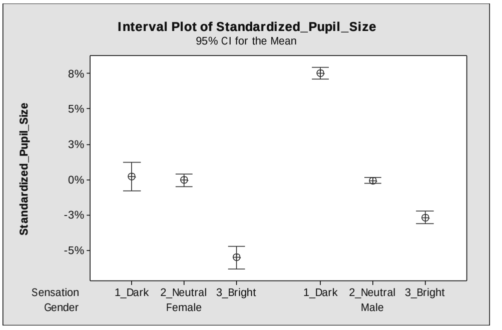


Figure 9. Comparison of overall standardized pupil size per visual sensation between myopic groups.

Figure 10. Comparison of overall standardized pupil size per visual sensation between gender groups.

4. CONCLUSIONS

Pupil sizes that are controlled based on the principles of the human autonomic nervous system, vary depending on individuals. Many existing references support the concept that visual sensations and pupil sizes are also different, depending on physiological characteristics. As an early stage study, this research conducted experimental tests using 15 human subjects in an environmental chamber, and investigated the differences in pupil sizes caused by different visual sensations resulting from varied luminance intensities. A comparison study between different subject groups by gender, age, myopic, gender, and eye color were also conducted. Data analyses showed that, overall, there were significant differences in pupil sizes with various visual sensations. In particular, the average pupil size between two different visual sensations was estimated to have a 5% or higher variance. However, the female and the no-glasses groups did not show any consistent pattern in the whole dataset (i.e., a stable pupil size with at neutral sensation, and larger sizes in a range of dark sensations, or vice versa.

There were several limitations to this research that warrant further investigation. As shown in Table 1, the subject sample size was not sufficient to support a robust statistical analysis. In spite of the significance of physiological characteristics that affect pupil sizes, the inadequate sample sizes may weaken the study findings, and may not validate the research discoveries. Therefore, additional experiments with larger samples and a balanced-size subject group should be included in a future study.

In addition, even though each experiment began by the test subjects receiving instructions about how to correctly report the perceived visual sensations and comfort levels, some subjects were confused by the surveys. For example, a higher sensation was reported, in spite of lighting conditions that had lower illuminance or luminance levels. Such inconsistent answers jeopardized the analyses of relationships between visual sensation and visual comfort levels, as compared to pupil sizes. Therefore, more simplified and systematic instructions are need for test participants in future studies.

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