Investigation of a real-time change of human eye pupil sizes per visual sensation condition

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Abstract: Lighting is the most crucial factor impacting an occupants' visual comfort in a building environment. However, most prevailing current lighting guidelines deriving from empirical values are designed primarily for paper-based tasks, rather than computer-based. In many cases, present guidelines have been reported that there is a limitation to meet the needs for a user's new task types. Above all, existing technical tools also have a limited function to evaluate a user's real-time visual perception which can be applied as an indicator to control a building lighting system. This research estimated each individual participant's visual sensations by analyzing pupil sizes and their change patterns since the human body have the physiological regulation ability which naturally minimizes the adverse effects of the surrounding environment on the human body. This study adopted a series of human subject experiments which were performed in an environmental chamber of USC. Based on a computer-based task which are most commonly performed in current offices, various ranges of ambient lighting parameters, including luminance (cd/m^2), illuminance (lux), contrast ratio, and UGR, were generated and controlled while each subject's pupil sizes were recorded. The experimental result data were statistically analyzed to identify a relationship between human visual sensations, lighting parameters, and also pupil sizes by ethnic origin and myopia condition. The research outcomes showed the potential use of pupil sizes for estimating an individual's visual sensation, and confirmed the principle as an applicable technology to integrate an environmental design and control system with the help of a real-time sensing device.

1.0 Introduction

In the contemporary society, people in America spend about 9/10 of time in the built environment (Codasco E, Demeter S.1995). Hence, the quality conditions of indoor environment become more significant than ever before. The work productivity and environmental health of occupants in a building are largely influenced by perceived sensations on the environment and ambient conditions, such as conditions of acoustic comfort, air, lighting and thermal (Choi J-H, Loftness V, Aziz A. 2012). Among those factors, the one that exerts the most significant impact on the visual comfort and sensation of an occupant is visual quality, since it is susceptible to and affected by the instantaneous impact's quality of lighting on users (Illuminating Engineering Society of North America 2010). According to some researchers, the percentage of occupants in buildings who are exposed to improper lighting conditions amounts to 65% (Irlen H. 2005). Those defective conditions, consequently, could lead to visual stress and glare problems in the environment of a workplace and potentially result in physical symptoms (like a headache and eye fatigue) and lower working efficiency. Therefore, proper lighting condition is of great importance to ensure the healthy state of occupants in a building and protect them from disease or injury related to eyes. The existing design guidelines, such as the IESNA (Illuminating Engineering Society of North America), have been developed by empirical and experimental methods in monitored lab tests; while those recommended guidelines are mostly for tasks that are paper-based instead of computer-based. 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, visual perception in relation to prevailing multi-screen workstation environment should also be taken into account. Discomfort resulting from contrast ratios and glare problems in the user's field of view from the inappropriate placement of monitors can also considerably impair on a person's productive capacity and a general sense of well-being in the work-space (Andrew Scott Linney 2008). More importantly, no functional characteristics of those existing technical tools can evaluate the real-time visual sensation of a user in a workplace that could be applied to lighting control system. All these defects may limit the successful adoption of current guidelines for application in real industry.

The questionnaire for visual comfort is a good way to evaluate the visual satisfaction. However, one weakness of this method is that it is a subjective way. An objective way to quantitatively evaluate the visual satisfaction should be considered. According to the biomedical research about the human body, the autonomous nervous system can naturally assist the body to react properly to minimize any perceived environmental stress. As part of the push/pull of the autonomic nervous system, the sympathetic and parasympathetic systems can control the pupillary dilator and sphincter muscles, which work together to control pupil size (Cassin B. 2011). Much literature has studied the potential of using pupil size. Some have supported the relationship between pupil sizes and visual sensations, and reports that pupil sizes vary physically depending on human physiological characteristics (Berman S, 1996; Green DG 1980). Several research projects have identified pupil size is related to different visual objects, such as wall color and illuminance (Winn B. 1994; Berman S. 1997; Choi J H, Zhu R. 2015). Some have analyzed the pupillogram can be performed easily to produce a real-time assessment of the subject's alertness (Morad Y, 2000). Therefore, by utilizing this mechanism, this research identified a relationship between human visual sensations, lighting parameters, and pupil size by adopting pupil size as a physiological signal which response to the real-time lighting condition. The final result of this research could be considered as a valuable reference for real-time lighting control in the human-building integration domain.

2.0 Methodologies

2.1. Human subject experiments

The author conducted a series of human subject experiments in an environmental chamber at University of Southern California (USC) campus to evaluate the relationship between human pupil sizes and visual sensation. The USC Internal Review Board (IRB) Office approved this study, and a total of 10 people were selected as voluntary human subjects for this experiment. Participants were recruited through flyers and electronic postings, most of them are on-campus students. Because of the diversity limitation of the campus population, the demographic information of subjects shows some limitations. Therefore, to get as unbiased results as possible, efforts were made to balance the sample sizes by critical human factors of visual sensation when created data pool, including gender, age, ethnic origins and glasses-worn condition. Table 1 listed the demographic information about participants. the questionnaire was adopted in this experiment to collect each subject's visual sensations at the end of each step of lighting condition. The subject was asked to report his or her visual sensation on a 7-point scale survey. It consisted of seven options ranging from "very dark (-3)" to "very bright (+3), with a "neutral" (0) mid-point.

Table 1: Demographic information about human subjects

	Gender		Age		Iris Color		Glass-worn	
	Male	Female	<25	≥25	Blue	Brown	Yes	No
Sample No.	4	6	7	3	2	8	5	5

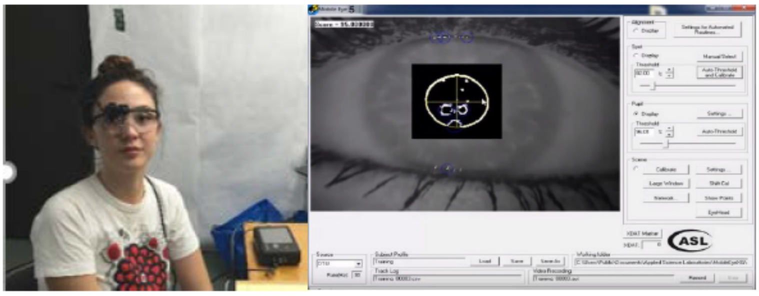

Figure 1: Photo of subject wearing the pupilometer and the software for pupil size data collection

2.2. Environmental chamber settings

The experiment will be carried out in the environmental chamber at USC watt hall, located on the basement floor. This physical condition allows producing the experimental desired lighting condition more ideally by using installed LED bulb, since there is no influence of daylight. The size of the entire chamber is 112"x120"x95", very close to the size of an ordinary workplace, which is the experiment environment wanted to be simulated. To obtain consistent environmental conditions, the ambient thermal, acoustic and air quality conditions were carefully controlled throughout the experiment. The air temperature, relative humidity, and CO_2 during the experiment were ranged from 24.5 ± 0.5℃, 32 ± 2.5%, and 610 ± 35 ppm, respectively.

2.2.1 Illuminance Level

The chamber was equipped with 30 units of 9W 730 lumens dimmable LED light bulbs on the ceiling surface. LED light exerted no impact on the thermal environment of the laboratory since it does not generate thermal radiation. The color temperature was set around 5000 K, which is very common in the daily work environment and the generated lighting intensity on the workstation surface ranged from 50 lux to 1400. The illumination adjustment can be achieved using an analog regulator with an illumination interval of 150 lux, which is the minimum perceptible illumination change demonstrated in the previous study (J.-H. Choi, Zhu, and Johnson 2013). The overall luminance was also considered in this experiment and measured by Photolux 2.1. The estimated correlation index was 0.99, with a p-value equals to 0.000. Since there is a strong linear relationship between overall luminance and illuminance, all luminance data were given by using the illuminance measured during this experiment.

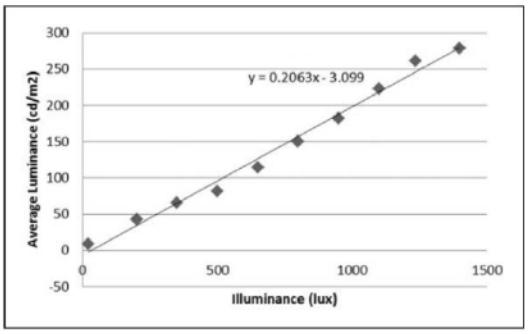

Figure2: The correlations between illuminance and the average luminance of the experimental settings.

2.2 Contrast Ratio and UGR Value

In this experiment, the contrast ratios for visual comfort refer to the contrast between the task area luminance and glare source which is TV screen located right behind the task computer screen. The contrast ratios and UGR value used were determined by measuring the luminance of the computer screen, TV and surrounding surfaces (e.g. walls) using fish-eye lens camera (Model: Nikon Coolpix 8400). The luminance of the computer screen was calculated by Photolux software and set constant at a measured luminance of 75 cd/m^2. A number of extensive studies concluded that a luminance ratio of 3:1 between the task & nearby surroundings is desirable for visual comfort (Osterhaus, 2002). Generally, the UGR values are defined in steps of 13, 16, 19, 22, 25 and 28. The UGR limits of lighting products for various environments that should not be exceeded 16 for technical drawing and 19 for reading, writing, training, meetings, computer-based work (Liht 2016). The experimental settings should be able to validate the rationality of the recommendations. Based on this principle, also considered the actual situation of the laboratory, the result of the realizable contrast ratio was picked as 1/4.25, 1/1, 6.4/1 and UGR values were 18.1,12.2 and 14.7, respectively.

Table 2: realizable contrast ratio, related parameters and TV settings

NO.	Contrast ratio	Laptop luminance (cd/m^2)	TV luminance (cd/m^2)	TV Darkness	UGR
1	1/4.25	75	318	12%	18.1
2	1/1	75	73.2	60%	12.2
3	6.4/1	75	11.6	Turn off	14.7

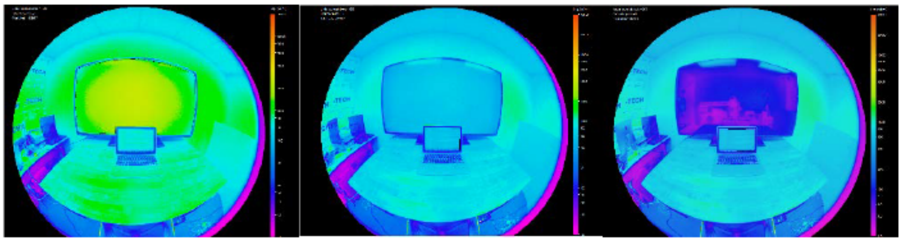

Figure 3: TV and computer screen luminance false color
(contrast ratio of computer screen to TV: a. 1/4.25; b. 1/1; c. 6.4/1)

2.3 Experimental Apparatus

Multiple sensory devices were selected to measure data for the human subject experiment. A mobile pupillometer was selected to measure and record a subject's pupil sizes change automatically (Model: Mobile-Eye, manufacturer: ASL). The device is a wearable sensor, combine two high-resolution digital cameras, one that records the scene image and the other, the participant's eye. These images and data recorded are then integrated into two documents, a single video recording and an excel document recording participant's pupil size 30 times every second. For the study, sensing frequency was set at one second to find significant changes in pupil sizes. Illuminance data were measured by light meters (Model: HHLM-2) which equipped on the surface of the table in the middle which is the main point of people's visual range.

2.4 Experimental Procedure

The experiment consists of three rounds of experiments and only one subject at a time. One fixed contrast ratio was set in each round experiment as illuminance level changed from 50lux to 1400lux with a 150lux interval. See the previous section for specific parameter settings. During the experiment, the light was changed from dark to bright gradually, this procedure is also known as light adaption which usually only takes human eyes less than 1 minute to adapt to the new lighting condition. Thus, each illuminance level step was designed with 2 minutes for stabilization and 1 minute for data collection. The whole experiment lasted one hour and thirty minutes, all data, such as illuminance, pupil size will be automatically recorded by the devices. The subjects were assigned some simple computer-based work during the test, such as reading and typing, at the end of each illuminance level changed; the subject was required to report his or her visual sensation by filling the 7-point scale questionnaire which mentioned in 2.1. All choice should be made based on subjects' perceptions about the lighting condition during the final 1 min. Overall procedures illustrated in figure 4.

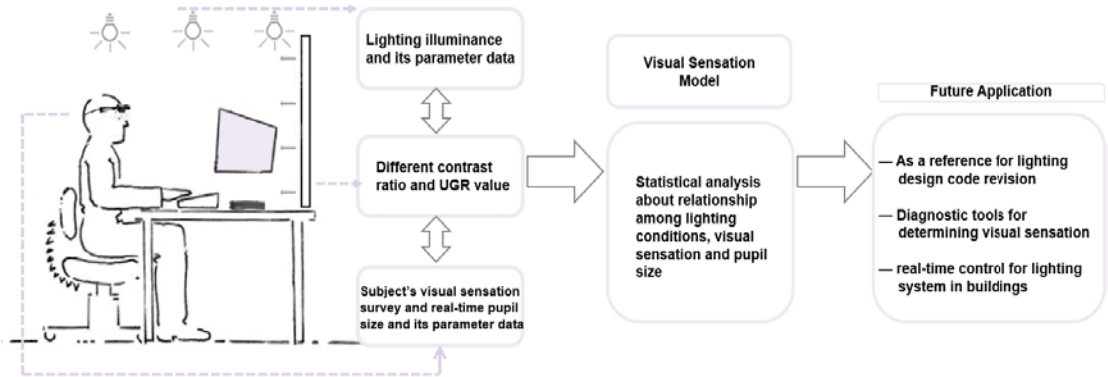

Figure 4: Procedures for data acquisition, expected outcomes and potential applications

3.0 Results and Discussion

3.1. Pupil Size per Sensation by Contrast Ratio

To examine the effect of the different contrast ratio on pupil size changes per visual sensation, each subject was asked to perform a comparative test under different contrast ratio lighting conditions while remaining other conditions unchanged. Figure 5-7 illustrated pupil size difference per sensation by three different contrast ratios, 1/4.25,1/1, 6.4/1 respectively. Overall speaking, compared the same level of a visual sensation among three different contrast ratio group, the average pupil size increases with the reduction of the background screen brightness. For example, the average pupil size is around 62 pixel for sensation 'very dark' (-3) when the contrast ratio is 1/4.25. By contrast, the average pupil size is around 65 and 69 pixels when the contrast ratio is 1/1 and 6.4/1 respectively.

The t-test of the pupil sizes of very dark sensation (-3) between 1/4.25 contrast ratio, 1/1 contrast ratio and 6.4/1 contrast ratio group revealed a p-value of 0.000,0.858 and 0.000 respectively, which the mean of 1/4.25 contrast ratio group significantly differs from the other two group. The one-way analysis of variance (ANOVA) test showed a statistically significant p-value that was lower than 0.05 for each group. Visual sensation could be more directly recognized as 'dark' which grouped -3, -2 and -1 level, 'neutral' which is 0 and 'bright' which included 1,2 and 3 level. The interval lines are distinct from each other, and the length of neutral sensation and bright sensation are much shorter than dark sensation, which indicates that pupillary dilator and sphincter muscles have greater adjustment range in order to find suitable pupil size in dark compared to neutral and bright environment in which the pupil size is more stable.

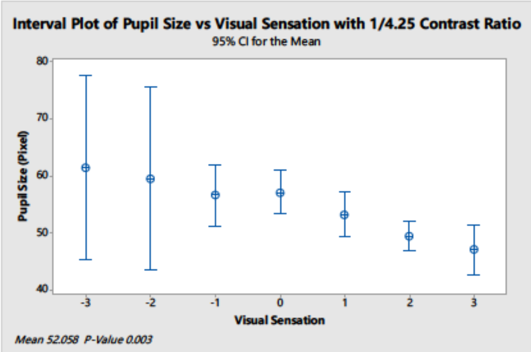

Figure 5 Interval plot of pupil size per visual sensation to 1/4.25 contrast ratio

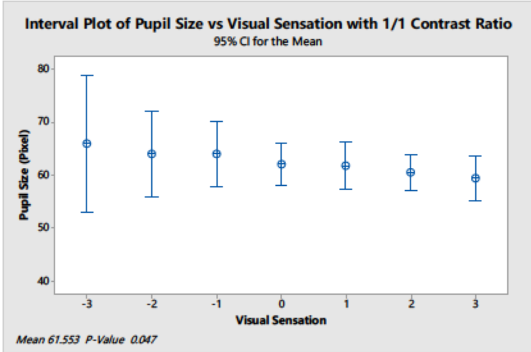

Figure 6 Interval plot of pupil size per visual sensation to 1/1 contrast ratio

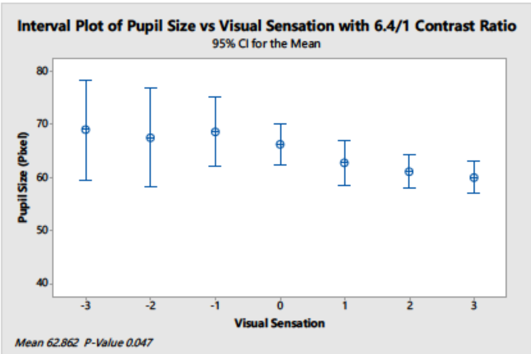

Figure 7 Interval plot of pupil size per visual sensation to 6.4/1 contrast ratio

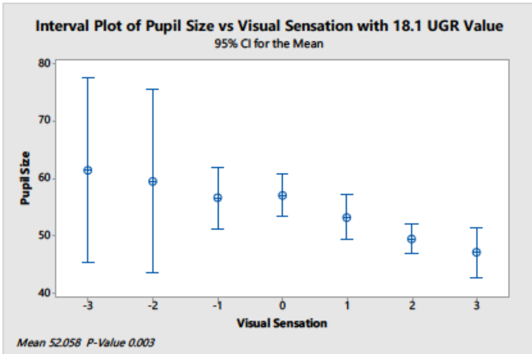

Figure 8 Interval plot of pupil size per visual sensation to 18.1 UGR value

3.3 Pupil Size per Sensation by UGR Value

The study also compared the pupil size change patterns by different UGR value. Figure 9-10 illustrated pupil size difference per sensation by three different UGR values, 18.1,12.2, 14.7 respectively. Although the analysis of variance (ANOVA) tests of all groups show p-values lower than 0.05, which means statistically significant, the actual differences in pupil sizes between visual sensation levels in the 12.2 UGR value and 14.7 UGR value group could be more difficult to detect in reality compared to 18.1 UGR group. In other words, pupil size is more stable with lower UGR value.

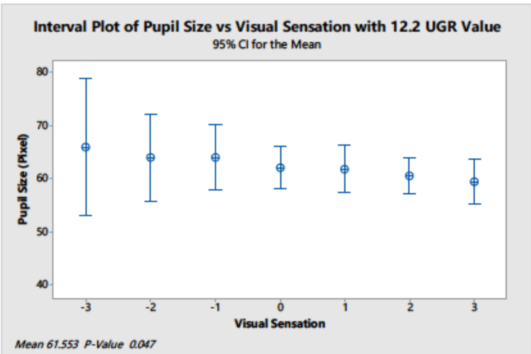

Figure 9 Interval plot of pupil size per visual sensation to 12.2 UGR value

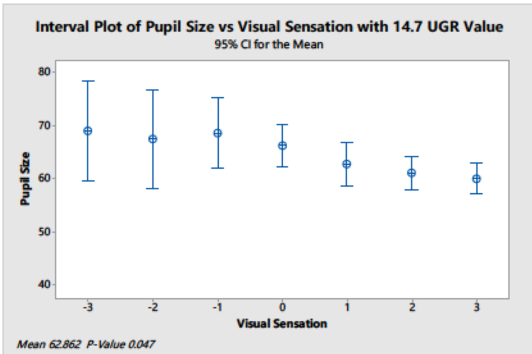

Figure 10 Interval plot of pupil size per visual sensation to 14.7 UGR value

4.0 Conclusion

As an early study, this research conducted a human subject experiment with ten subjects in an environmental chamber and investigated the differences in pupil sizes caused by different visual sensations due to varied contrast ratio and UGR values. Overall, significant differences in pupil sizes with various visual sensations could be told when grouped by contrast ratio and UGR value as well. These findings indicated that pupil size has the potential to be a viable indicator of preferred lighting conditions.

For each contrast ratio group, the adjustment range of pupil size is always greater in the dark compared to a bright environment. Compared to three contrast ratio group, the data showed that the adjustment range of pupil size reduced as the contrast ratio narrowed down between backlit and task screen. The amplitude range is relatively minimal when the backlit turned off. The adjustment range of pupil size was significantly greater in the dark than in the other two groups the when contrast ratio was 1/4.25. This also happened in the group UGR value equaled to 18.1 which is very close to the upper limit value 19. The eye requires a greater range of adjustment of the sphincter to achieve the proper pupil size, which may be one of the factors leading to eye fatigue. Also, there is no statistically significant difference between 1/1 contrast ratio and 6.4/1 contrast ratio group. Therefore, recommended value mentioned in chapter 2.2 have certain rationality based on the discussion above.

In addition, considering that this is a human subject experiment, the representativeness of the sample should always be taken into account. However, subjects selection was limited by campus population as shown in table 1. Therefore, future studies should include additional experiments on large samples and a balanced population of subjects.

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