Building and Environment 88 (2015) 73–81

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Investigation of the potential use of human eye pupil sizes to estimate visual sensations in the workplace environment

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A R T I C L E I N F O

Article history:
Received 5 August 2014
Received in revised form
4 November 2014
Accepted 24 November 2014
Available online 5 December 2014

Keywords:
Visual comfort
Bio-signals
Lighting condition
Workplace
Indoor environmental quality
Individual control

A B S T R A C T

Building occupants' environmental comfort and physiological health conditions are significantly affected by workplace environmental quality, such as lighting, thermal, air, and acoustic conditions. Of all of these factors, lighting quality is the most significant in relation to the occupants' visual comfort and health, since its effect is almost instantaneous, and it is vulnerable due to its immediate sensitivity. This research investigated the possibility of using human eye pupil sizes to estimate visual sensations in office workplace environments. The human body, as a biological mechanism, naturally makes unconditioned responses using the parasympathetic nervous system in multiple physical organs, including pupils in human eyes. Based on this physiological principle, a human body automatically reacts to ambient conditions to minimize any environmental stressful condition. This study adopted this principle as a key factor for analyzing pupil sizes and their change patterns to assess each individual subject's visual sensations while generating various ranges of ambient lighting conditions in an environmental chamber. The chamber is located at the University of Southern California where researchers conducted a series of human subject experiments. The collected data were analyzed using statistical tools for interpreting research findings. The data were grouped by the subjects' gender, age, glasses-worn, eye color, in order to identify any differences in pupil sizes and change rates, depending on the physical characteristics of each individual. These research findings indicated that the use of pupil sizes to assess a subject's visual sensations has potential and would be applicable to individuals, regardless of their physical characteristics.

1. Introduction

As modern people spend 90% of their time in a built environment in the U.S. [1], the role of indoor environmental quality conditions is more impressive than in the past. The environmental health and work productivity of a building's occupants are sensitive to and are affected by ambient conditions and perceived environmental sensations, such as thermal, lighting, air, and acoustic comfort conditions [2–4]. Of all of these factors, visual (lighting) quality is the most significantly related to an occupant's visual sensation and comfort as it is affected by and susceptible to the quality of the lighting's instantaneous effect on users [5,6]. Several researchers have reported that 65% of building occupants are exposed to inappropriate lighting conditions and, as a result, these conditions can cause glare problems and visual stress in a workplace environment [7–9]. This defective condition has the potential to contribute to lower work productivity and physical symptoms, such as eye fatigue and headaches [10–13]. These inadequate environmental conditions have been estimated to result in a $2700 loss per year in the health/work productivity of each user in an office workplace [10,14]. Accordingly, adequate lighting conditions are extremely critical to assure the good health of a building's occupants and to ensure freedom from eye-related injury or disease. Current industry guidelines, such as the Illuminating Engineering Society of North America (IESNA) [5], have been designed based on experimental and empirical approaches in supervised laboratory tests, and those recommended are mainly for paper-based tasks, rather computer-based tasks. Today's technology- oriented work environment has led to frequent changes in office layouts, resulting from high turn-over rates, that have cost approximately $200 per employee each year [10]. This phenomenon has hindered the use of static computational lighting quality diagnostic tools, such as a lighting contour image, and a computational simulation program. Most of all, these current technical

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http://dx.doi.org/10.1016/j.buildenv.2014.11.025

tools have no functional feature to assess a workstation user's visual sensation in real time that can be applicable to building lighting system controls.

There have been many researchers who have reported different levels of individually preferred lighting intensity, depending on such factors as gender and age [15–20]. One of the author's previous research efforts also supported these existing literature findings with measured and surveyed data [2]. In both instances, individuals reported different visual sensations in similar lighting conditions, and requested different lighting levels in spite of the fact that they were performing the same type of task in an office building.

Pupils dilate and shrink, largely in response to variations in light. This is controlled by the pupillary dilator and sphincter muscles that oppose each other to control pupil size; these muscles are innervated, respectively, by the sympathetic and parasympathetic systems, as part of the push/pull of the autonomic nervous system [21,22]. This natural physiological system allows a human physiological condition to remain stable while minimizing changes in the ambient environment, such as the reduction of pupil size in bright light, and perspiring to minimize thermal stress. Based on the principle of utilizing the natural physiological conditions of human eyes, several research projects have been conducted to identify pupil size reactions to different visual objects, such as wall color, reflections, and illuminance. Berman et al. [23,24] examined the effect of pupil size on the letter size-acuity function based on the use of “accuracy of reading” as an acuity measure, and established various lighting spectrums to investigate the pupillary spectral response to the generation of various luminance conditions within a limited range. Mojtaba [25] conducted the visual acuity test under various color temperature conditions while monitoring the pupil sizes of subjects' eyes. In particular, the relationships between visual acuity and pupil sizes have been studied for decades in the domain of ophthalmology [26–29]. There are recent research projects that focus on pupil sizes, but they have mainly been concerned with pupil sizes affected by ophthalmological treatments [30–32]. As such, most existing research topics, regarding pupil sizes, have heavily relied on physiological reactions to visual stimuli, fatigue, and visual performance as a consequence of pupil size changes, with little integration with pupillary responses to visual sensations (or comfort), in spite of the potential for adoption as a visual sensation index. As discussed above, in the building environment domain, visual quality is one of the significant IEQ components, especially in a workplace environment where the health and work productivity of the occupants are critical. Thus, this research investigated the potential use of pupil sizes to assess a user's visual sensation in response to the workplace lighting environment, as a principle for human-building interaction.

2. Methodologies

2.1. Human subject experiments

To assess the correlation between human pupil sizes and visual sensation, a series of experiments using human subjects were conducted in an environmental chamber, located at the University of Southern California (USC). The user study was approved by the USC Internal Review Board (IRB) Office, with 20 subjects participating in the test, most of them University students. The subjects were recruited, based on consideration of their physical condition, to balance the sample sizes by gender, age, and ethnic origins. Their ages ranged from 21 to 54, while most of the subjects were Caucasian (sample size: 8) and Asian (sample size: 12), due to the limited diversity of the campus population. Table 1 summarizes demographic information about the participants.

Table 1
Demographic information about human subjects.

Parameters	Attributes	Male	Female
Age	Junior (Age <25)	6	5
	Senior (Age >25)	6	3
Eye color	Blue	4	0
	Brown	8	8
Glasses-worn	Yes	5	4
	No	7	4

2.2. Environmental chamber

The selected environmental chamber is located on the basement floor of a campus building at USC. This isolated place on the underground level does not provide any daylight to the space, so this physical condition allowed the authors to generate intended lighting conditions using already installed electric light bulbs. As illustrated in Fig. 1, the chamber was equipped with 15 units of 9W-LED light bulbs on the ceiling surface. The LED light was intentionally selected to prevent any distortion of thermal quality due to a bulb's thermal radiation. The selected light temperature was around 2700 K, and the generated lighting intensity, i.e., illuminance (lux) on the workstation surface ranged from 50 lux to 1450. The change level could be selected using an analog controller, but 150 lux was adopted as a change interval because it was validated as a perceivable change interval during the pilot study [33]. The study also considered overall luminance in the major vision field of subjects in the experimental setting. In the chamber environment, the overall luminance measured in the test subject's visual field was significantly affected by the generated illuminance, and showed an almost linear relationship with the illuminance, as shown in Fig. 2. A linear relationship was found between illuminance in the workstation and the average overall luminance. The estimated correlation index was 0.99, with a statistical significance of $p = 0.000$. Since the study was focused on the user's physiological responses to each lighting condition (which was controlled as a function of lighting intensity), illuminance was selected as a major lighting parameter control based on the linear relationship for analyzing the human factor data.

The ambient thermal, acoustic, and air quality conditions were consistently controlled in each experiment to achieve a consistent environmental condition. The overall ranges of the air temperature, relative humidity, and CO2 during the experiment were 23.5 ± 0.7 °C, 33 ± 2.5%, and 620 ± 35 ppm, respectively.

2.3. Experimental devices and settings

For the human subject experiment, the study adopted multiple sensory devices. To measure a subject's pupil sizes, a mobile pupilometer was used (Model: Mobile-Eye, manufactured by ASL), as shown in Fig. 3. The device is a wearable sensor, like a light-weight ski goggle, and the pupil sizes could be measured and recorded at a frequency of 30 Hz. It detected the size of a pupil by a micro-camera facing the subject's eye while tracking the path of eye movement. The collected data was automatically forwarded to a database installed in a data acquisition computer in the chamber. For the study, one second was adopted as the sensing frequency to find significant changes in pupil sizes. To measure illuminance levels on the workstation surface, three illuminance meters (Model: HHLM-2) were installed at the left side, center, and right side of the table's horizontal center line, and the averaged illuminance was selected as representative data for the illuminance condition. Overall, during the experiments, the estimated deviation of illuminance was approximately