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The Effect of Light Distribution of LED Luminaire on Human Ocular Physiological Characteristics

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ABSTRACT Light-emitting Diode (LED) has been considered as one of the new generation lighting sources with several merits such as high efficiency, high reliability, long lifespan, high-speed response, and energy saving. The optical performances of an LED luminaire, such as illuminance, luminance, correlated color temperature, and spectra power distribution, determine the lighting environment which can affect the human ocular physiological characteristics. To investigate the effect of optical performances on human vision, previous studies have assessed the subjective perception based on questionnaires. In this paper, we propose a novel method based on the aberrations and accommodations data from 150 human factor measurements on a total of 25 participants. The results show that: 1) optical performances of the LED luminaire have an influence on ocular physiological characteristics during the visual task duration, which can be quantized by the variations of physiological parameters; 2) the desk illuminance and light distribution curve are selected in this study as the optical parameters. The variations of ocular physiological characteristics reach the minimum values when the desk illuminance is 550 lux and the light distribution curve is large beam angle; and 3) ocular physiological characteristics are more sensitive to the light spatial distribution compared to the light quality. Thus, the proposed assessment method based on variations of ocular physiological characteristics in this paper is promising as one of the guidelines for the design and optimization of the LED luminaires.

INDEX TERMS LED luminaire, optical performance, human vision, ocular physiological characteristics, lighting environment assessment.

I. INTRODUCTION

With ever-increasing competences in lumen efficacy, color consistence and durability, LEDs have gained a wide range of applications including indoor lighting, commercial lighting, automotive lighting, healthcare lighting, intelligent lighting, etc [1]–[4]. For indoor lighting applications, previous researches usually focused on energy efficiency and environment protection, however, these two aspects seem not enough without taking human factor into consideration. An increasing number of scholars have begun to express concerns about visual comfort in various lighting environments, which is also known as lighting-induced visual fatigue [5]–[7]. For a certain lighting environment, there are three dimensions that could describe its characteristics: light quality (illuminance [8]–[10], daylight factor [11]–[13], daylight autonomy [14]–[16], etc.) and light distribution (illuminance uniformity [17], [18]). For a luminaire, optical performances on light quality and glare are applicable, such as illuminance, luminance, correlated color temperature (CCT) [19], [20], and spectra power distribution (SPD) [21], [22].The light distribution index is uncommon for luminaire products but often employed in indoor lighting. These optical indices could cover the overall characteristics of lighting environment, and there are corresponding standards for assessments, most of which are based on subjective perception of discomfort.

Perception of discomfort or fatigue generally presents as ophthalmic acid, lacrimation, and blurred imaging, in which the ophthalmic acid and lacrimation are related to strain of ciliary muscle, the blurred imaging is caused by failure of lens focal distance adjusting by ciliary muscle. Short-term visual task in various lighting environments, adjusting ability of ciliary muscle presents different, resulting to different variations of lens shapes. In a human eye measurement, adjusting ability of ciliary muscle can be represented by the accommodation (ACC) [23]–[25], and the change of crystalline lens could be effectively indicated by the high order aberrations (HOAs) [26]–[28]. Consequently, fatigue perceptions of human eye are always related to the ocular physiological parameters of both ACC and HOAs. The direct measurement on discomfort perception with the method of subjective questionnaire scoring is often susceptible to the human emotion and cognition, thus it usually provides several instable results. Ocular physiological parameters of ACC and HOAs are relatively more stable and often used in clinical diagnosis. Therefore, it is promising to obtain more accurate results of visual discomfort or visual fatigue by the measurement of ocular physiological parameters of ACC and HOAs.

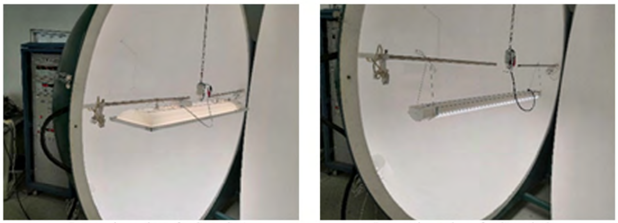
In various lighting environments with the same duration, human eyes tend to have different reactions, which could be reflected by different variations of ACC and HOAs. There is likely to be a correlation between optical performances of luminaire and variations of ocular physiological parameters (ΔACC and ΔHOAs) in the constant duration. For a luminaire, optical performance indices consist of light quality and light distribution, in which the light quality depends on single luminaire only, but the light distribution relies on not only single luminaire but also the distribution. In this study, it is expected to compare influences of different luminaire optical performances on human vision, and figure out the correlation between luminaire physical indices and human ocular physiological characteristics. The contribution of this work is that the optical performances of LED luminaires are quantitatively assessed in objective method based on physiological parameters instead of subjective perception. The method and results in this study are applicable to the field of lighting and displaying, and guide the research and development of artificial lighting sources.

The remaining of this paper is organized as follows: in the section 2, we measured and analyzed the optical performances of two luminaires and performed the human factor experiments. Section 3 discusses the relation between optical indices of luminaires and ocular physiological characteristics. Finally, the concluding remarks are presented in Section 4.

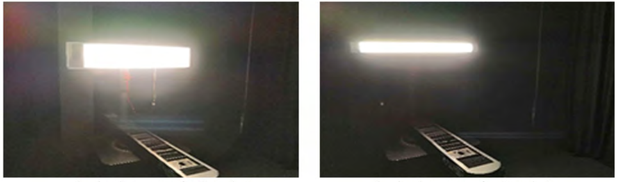
II. MATERIAL AND METHOD

A. LIGHTING ENVIRONMENT CONSTRUCTION

In this study, we expect to compare the influence of luminaire optical performances on human vision by the ΔACC and ΔHOAs. It is necessary to measure the ΔACC and ΔHOAs of humans when they stay in a lighting environment with a certain duration. In this lighting environment, the lighting indices, including light quality and light distribution, should be measured in advance. The light quality depends on SPDs of luminaires and light distribution relies on the light distribution curve as well as luminaire's distribution.



Integrating sphere for Sample 1 Integrating sphere for Sample 2



Gonio photometer for Sample 1 Gonio photometer for Sample 2

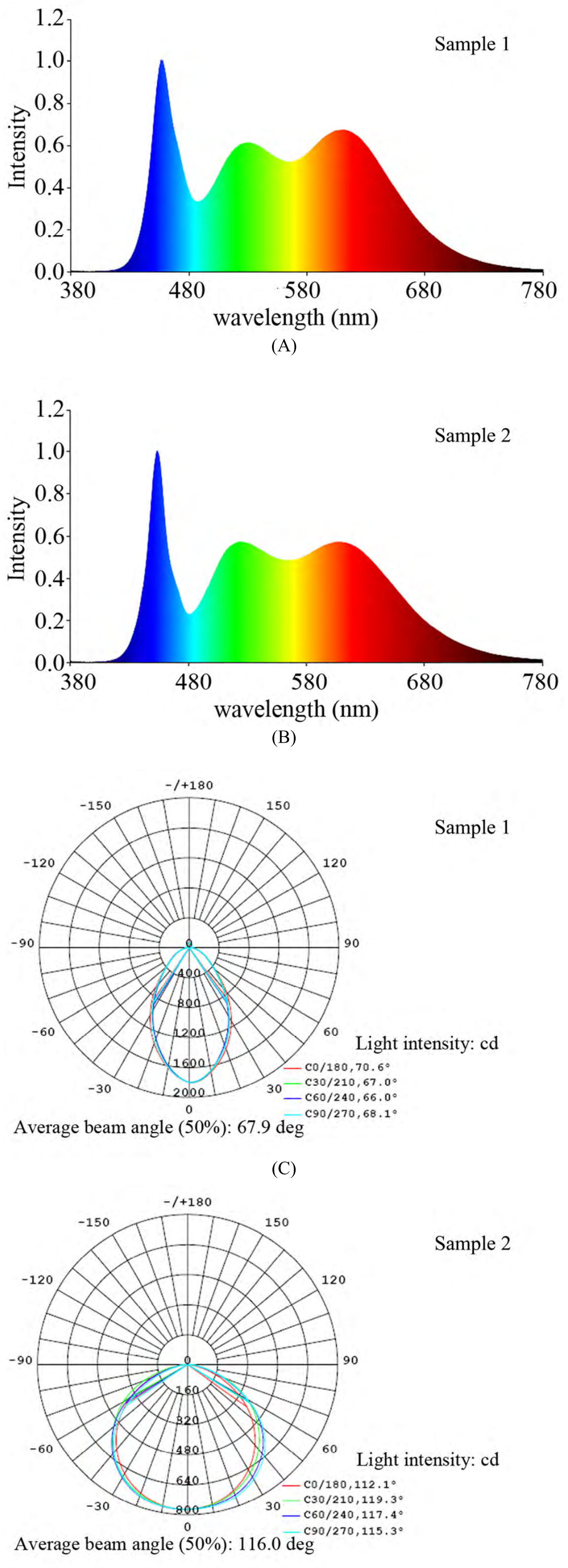
FIGURE 1. The optical performances measurement systems including Integrating sphere (EVERFINE YF1000) and Gonio photometer (EVERFINE GO-2000A-V1).

TABLE 1. Detailed information of luminaire lighting parameters.

LED classroom lamp	Sample1	Sample2
Lighting pattern	Direct	Indirect
Light quantity (lm)	2146	1910
Luminous Efficiency (lm/W)	60.57	87.96
CRI	94.7	94.7
CCT (K)	4667	4866
Beam angle (degree)	67.9	116
Power factor	0.972	0.948

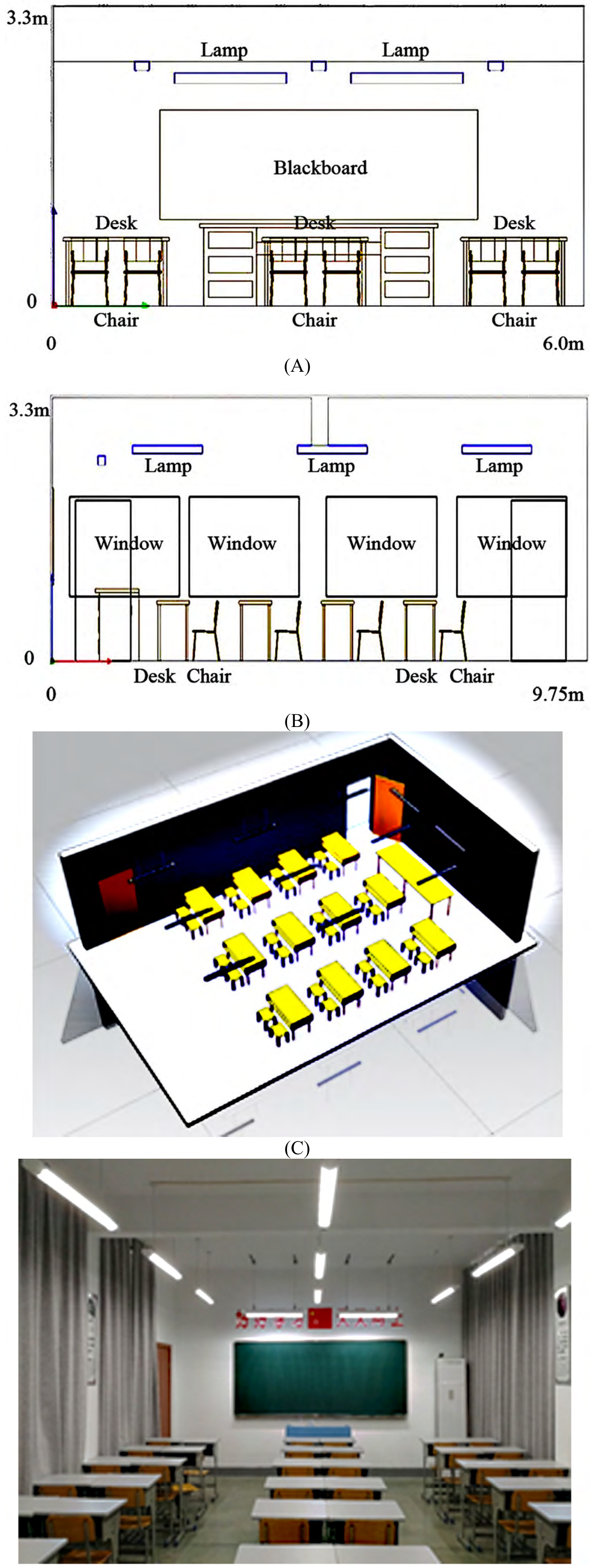
To construct the lighting environments, we used two kinds of classroom luminaires marked with Sample 1 and sample 2. As shown in Figure 1, the optical performances of LED luminaires were measured by the Integrating sphere (EVERFINE YF1000) and the Gonio photometer (EVERFINE GO-2000A-V1). Measurements were performed according to the standard CIE 127:2007 [29]. The measurement results are shown in Table 1. The SPDs and light distribution curves of two luminaires are shown in Figure 2 (A∼D), which indicates that these two luminaires have the similar SPD. There are three peak wavelengths in the blue, green and red sections where the greenlight section presents similar intensity to the red light section. For the light distribution curves of two luminaires, Sample 2 presents an obviously larger average beam angle than sample 1 (nearly two times in degree). For the light intensity in 0 degree, sample 1 is obviously higher than sample 2 (nearly two times in cd).

In a lighting environment, the light distribution relies on two factors: the light distribution curve of single luminaire and the position distribution of all luminaires. In this study, we compared the above two classroom luminaires with different light distribution curves. For simplicity, we kept the luminaires' position distribution the same, which is shown



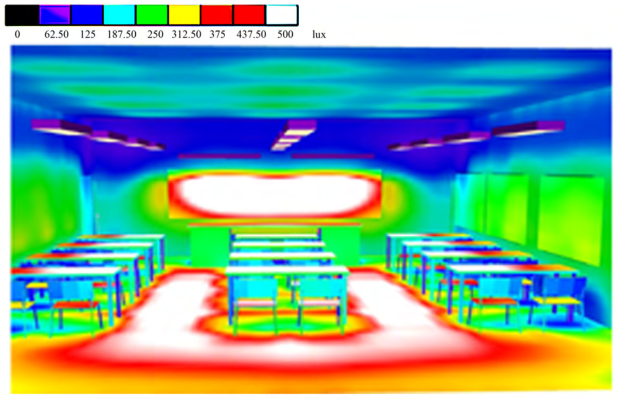
(D)

FIGURE 2. Optical performance measurement results of two luminaires. (A) Sample 1's spectra. (B) Sample 2's spectra. (C) Sample 1's light distribution curve. (D) Sample 2's light distribution curve.

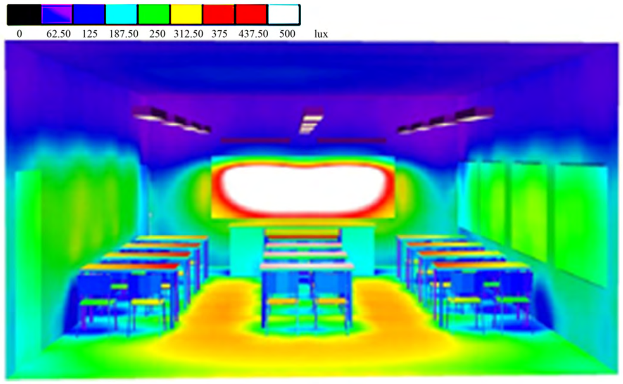


(D)

FIGURE 3. The design of lighting environment of (A) back view, (B) left view, (C) 3D model and (D) real photo.



Sample 1
(A)



Sample 2
(B)

FIGURE 4. The simulated light distributions of lighting environment for (A) Sample 1 and (B) Sample 2.

in Figure 3 (A∼D). Desks and chairs are distributed uniformly as a 3×4 matrix. There are two doors (front and back) and two windows (with grey curtains) on the left wall of the classroom, and four windows (with grey curtains) on the right wall. The blackboard is set in the front of the classroom. As shown in Figure 4, we simulated the light distributions in the designed lighting environments with two different luminaires, which presents the different light uniformities in this environment.

B. HUMAN FACTOR EXPERIMENT

Measurement is performed on 25 participants who are inspected and ensured to be without oculopathies such as cataract, heterotropia or amblyopia (Table 2). Light-induced visual fatigue is a process-related accumulation effect. Based on this fact, we design a quantitative evaluation method of light-induced visual fatigue by physiological parameters measurement. First, all participants are told to close eyes for 15min to reach the optimal and stable status. Second, measurements are performed on participants for the collection of physiological parameters data. Third, participants are guided to execute the visual task for 45min. According to the different causes of visual fatigue, the visual task is divided into two types: lighting type and displaying type. For lighting type, experimental environment is constructed according to the standard ISO 8995, and the visual task content is Landolt rings counting. The duration is designed 45min because most individuals have got accustomed to this duration since childhood in school. Primary and middle schools set 45 min as the duration of a class, and TV series also set 45min as the duration of an episode. In this study, our aim is to evaluate light-induced visual fatigue. Light influence on visual fatigue is accumulated during the 45min duration, and there will be a variation of visual fatigue degree during this period.

TABLE 2. Detailed information of participants.

Item	Information
Participant total number	• 25
Age distribution	• 23~35 (average 30)
Diopter distribution	• 40%: 0 ~ -1.00D • 40%: -1.00D ~ -3.00D • 20%: -3.00D ~ -5.00D
Visual acuity distribution	• 40%: 0.8 • 60%: 1.0
Anisometropia above 2.5D	• <5%
Intraocular pressure range	• 14~20

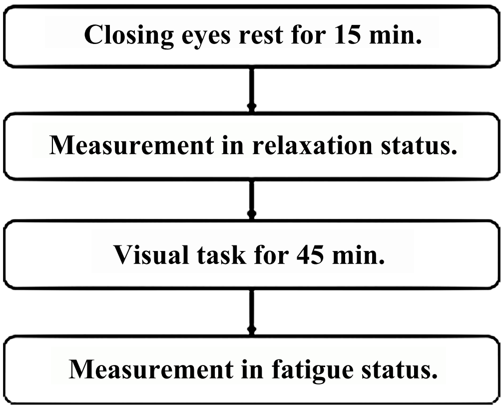


FIGURE 5. Detailed information of experimental process.

Measurement process is shown in Figure 5. In our human factor experiment, the measurement is performed for five days in the lighting environment of Sample 1 lamp. In the classroom equipped with Sample 1 lamps, there are various desk illuminances for desks in different locations. We select 350 lux, 450 lux and 550 lux as illuminances for measurement. In another five days the measurement is performed in the lighting environment of Sample 2 lamp. In the classroom equipped with Sample 2 lamps, desk illuminance also varies with desk location. It is widely accepted that desk illuminance of 550lux is appropriate for classroom reading, but the conclusion is obtained by subjective perception. In this study, we expect to evaluate influence of desk illuminance on human eye by objective method based on ocular

TABLE 3. Detailed information of measurement process.

Item	Information
Content	• In five days: All participants execute Landolt rings counting for 45min in lighting environment of Sample 1 lamp (Desk illuminance: 350lux, 450lux, 550lux). • In another five days: All participants execute Landolt rings counting for 45min in lighting environment of Sample 2 lamp (Desk illuminance: 350lux, 450lux, 550lux).
Instruments	• ACC: NIDEK AR-1S (Calibrated by The Measurement Test Research Institute of Beijing, calibration certification No. DC18J-QQ000362) • HOAs: NIDEK OPD Scan III (Calibrated by The Measurement Test Research Institute of Beijing, calibration certification No.JC17C-AB010010) • PS: NIDEK AL Scan (Calibrated by The Measurement Test Research Institute of Beijing, calibration certification No. HD14C-QZ7196)

physiological parameters. Consequently, we select 350 lux, 450 lux and 550 lux as illuminances for measurement. Detailed information of the measurement is shown in Table 3.

In this study, we employ ΔACC and ΔHOAs as indicators of lighting environment influence. By measurement in relaxation status, we get initial values of ACC and HOAs. By measurement in fatigue status, we obtain final values of ACC and HOAs. When the final value is subtracted by the initial value, we could get the variation value. The absolute value of variation could represent the influence of lighting environment. By measurement, we can obtain three types of ACC values: ACC_{max}, ACC_{min} and ACC variation. ACC_{max} describes the optical power when ciliary muscle reaches the maximum tension. ACC_{min} describes the optical power without additional tension. ACC variation is the difference between ACC_{max} and ACC_{min}. ACC is measured by the instrument NIDEK AR-1S. During the measurement, participant set the chin and forehead to the specified location of the instrument, and stared at the image in the instrument. Images varied with time and values of ACC (average, maximum and minimum) would be collected automatically by the instrument. Aberration data were collected by NIDEK OPD Scan III automatically and present in the form of Zernike polynomials. Spherical component of high order aberration (the 12th term) originates from the expansion of Zernike polynomials. In the current study, we use ACC_{min} to reflect ciliary muscle strength. Consequently, ΔACC_{min} is used to describe variation of ACC_{min}. For simplicity, we note ΔACC_{min} as ΔACC. From the human factor experiment, we can obtain Zernike aberrations of the 1st∼35th terms. Only the 4th and the 12th term are independent from measurement angle, so the following analysis will concentrate on these two terms. We use HOA4 to represent the 4th term Zernike aberration, and HOA12 to represent the 12th term Zernike aberration. HOA4 (defocusing) and HOA12 (sphere aberration) are related to the shape of crystalline lens, so ΔHOA4 and ΔHOA12 could reflect deformation of the lens, thus describing the lighting influence. As a result, we employ ΔACC, ΔHOA4 and ΔHOA12 to describe light-induced visual fatigue.

PS (pupil size) data of participants in various light environments were also collected in this study, since HOA value tends to be influenced by pupil size, which is quite sensitive to lighting condition.

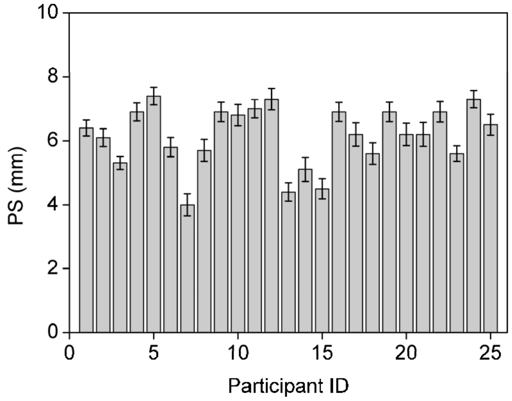


FIGURE 6. PS average value of each participant in the six measurements. Error bars represent deviations.

III. EXPERIMENTAL RESULTS

PS values of all participants were measured six times (in three illuminances and two luminaires). Optical performances of these six light environments were different from each other. PS value is quite sensitive to lighting condition of the light environment, but PS deviation of the six measurements for each participant is tiny compared to the PS value (Figure 6). It is implied that ocular physiological parameters (ACC, HOA4 and HOA12) are unlikely to be affected by PS values, since measurements on ocular physiological parameters (including PS and HOA) were performed in dark room in this study. PS is quite sensitive to surrounding light, and changes rapidly with lighting environment. During physiological parameter measurement, PS value reflects the lighting environment of the measurement place rather than the light condition of visual task place. Consequently, ACC and HOA results are unlikely to be influenced by PS values in our measurements.

A. DESK ILLUMINANCE

For artificial luminaires, there are several indices that are employed to describe light quality. In this study, measurements are performed in the same classroom. Luminaires used for lighting have similar SPD distribution, so CCT in the classroom hardly changes for each measurement. As a result, the major discrepancy of light quality is desk illuminance. Participants execute Landolt rings counting task in different desk illuminances, and their ocular physiological parameters (ACC, HOA4 and HOA12) vary during the task duration.

TABLE 4. Significance test results of ocular parameters between different illuminances. $*$ represents significance with $p<0.05$, $**$ represents $p<0.01$.

Comparison pair	Significance Test
350 lux & 450 lux, ΔACC, lamp1	t=0.744, p=0.464
**450 lux & 550 lux, ΔACC, lamp1	t=2.959, p=0.007
**350 lux & 550 lux, ΔACC, lamp1	t=5.012, p=0
350 lux & 450 lux, ΔACC, lamp2	t=-0.051, p=0.96
**450 lux & 550 lux, ΔACC, lamp2	t=4.08, p=0
**350 lux & 550 lux, ΔACC, lamp2	t=3.535, p=0.002
350 lux & 450 lux, ΔHOA4, lamp1	t=0.543, p=0.592
**450 lux & 550 lux, ΔHOA4, lamp1	t=3.569, p=0.002
**350 lux & 550 lux, ΔHOA4, lamp1	t=2.995, p=0.006
350 lux & 450 lux, ΔHOA4, lamp2	t=1.329, p=0.196
*450 lux & 550 lux, ΔHOA4, lamp2	t=2.665, p=0.014
**350 lux & 550 lux, ΔHOA4, lamp2	t=3.443, p=0.002
350 lux & 450 lux, ΔHOA12, lamp1	t=-1.178, p=0.25
450 lux & 550 lux, ΔHOA12, lamp1	t=1.349, p=0.19
350 lux & 550 lux, ΔHOA12, lamp1	t=1.161, p=0.257
*350 lux & 450 lux, ΔHOA12, lamp2	t=2.117, p=0.045
**450 lux & 550 lux, ΔHOA12, lamp2	t=4.28, p=0
**350 lux & 550 lux, ΔHOA12, lamp2	t=5.611, p=0

Variations of these parameters could reflect the lighting influence in the corresponding desk illuminance.

ACC describes accommodation ability ciliary muscle, and its variation reflects the reduction of ciliary accommodation ability due to lighting-induced visual fatigue. During the visual task duration, ΔACC reaches the minimum value in 550 lux both for Sample 1 lamp and Sample 2 lamp, as the box body in 550 lux is obviously lower than that in 450 lux and in 350lux although overlapping area exists (Figure 7A and 7B). Significance test is performed on ΔACC data, and results are shown in Table 4. It is implied that ciliary accommodation ability presents the minimum variation in the desk illuminance of 550 lux. For ΔACC in 450 lux and 350 lux, it is difficult to judge the larger one and the lower one, since medium lines of box plot are almost in the same level. For Sample 1 lamp, ΔACC data in 350 lux distribute relatively more scattered than those in 450 lux. But for Sample 2 lamp, ΔACC data in 350 lux present more concentrated distribution than those in 450 lux.Scattered or concentrated distribution is likely to depend on whether participants are serious in the task.

HOA4 and HOA12 describe imaging quality of human eye by quantifying image distortion formed in retina. Variations of HOA4 and HOA12 are unlikely to be perceived since the values are so tiny compared to origin values. However, HOA4 and HOA12 are directly related to crystalline lens shape, which is controlled by zonular lens connected to ciliary muscle. Consequently, it is suggested that ΔHOA4 and ΔHOA12 are related to the stretching status of ciliary muscle. With larger strain in ciliary muscle, fatigue is more likely to be accumulated. In the lighting environment of both Sample 1's and Sample 2 lamp, ΔHOA4 and ΔHOA12 reach the minimum value in 550 lux compared to the other two

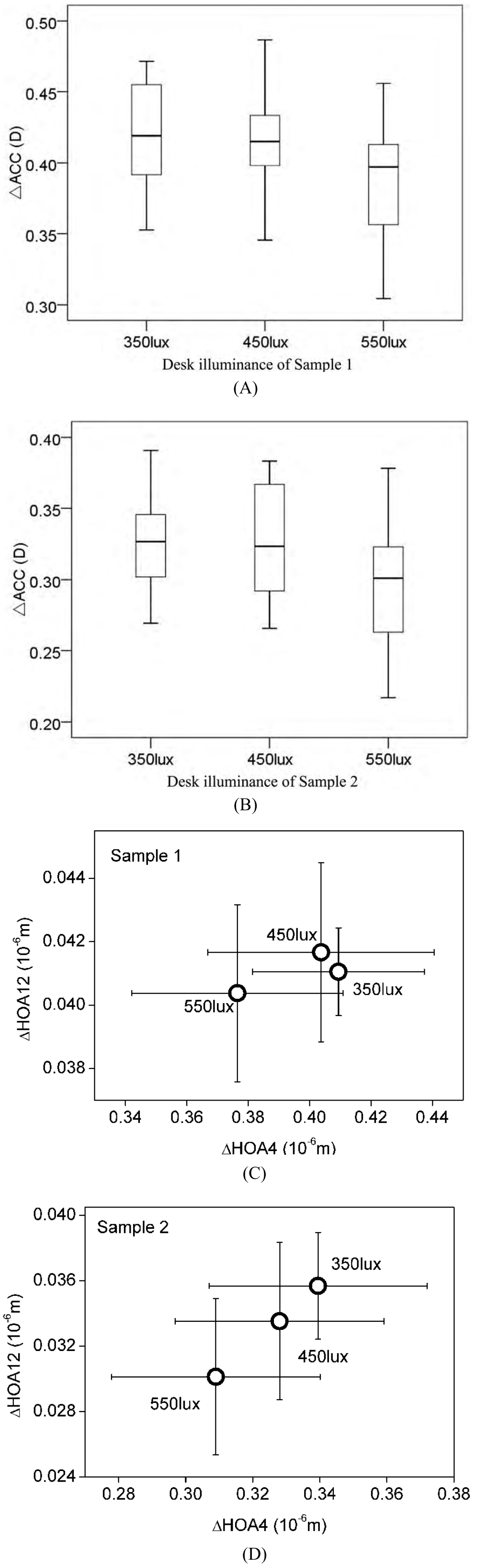


FIGURE 7. Comparison between different desk illuminances for (A) ΔACC in Sample 1 lamp, (B) ΔACC in Sample 2 lamp, (C) ΔHOA4 and ΔHOA12 in Sample 1 lamp and (D) ΔHOA4 and ΔHOA12 in Sample 2 lamp.

(Figure 7C and 7D). Significance test results on ΔHOA data are also shown in Table 4. It is indicated that lighting influences on HOA4 and HOA12 are the least. For ΔHOA12 in 450 lux and 350 lux, situations are a little different for Sample 1's and Sample 2 lamp. For Sample 1 lamp, the average value of ΔHOA12 in 450lux is higher than in 350 lux.In addition, error bar of ΔHOA12 in 450lux is so large that it covers values in 350 lux. For Sample 2 lamp the situation is on the contrary. It is inferred that ocular physiological parameters are not sensitive enough to distinguish lighting environments with desk illuminance of 350 lux and 450 lux.

B. LIGHT DISTRIBUTION CURVE

Light distribution curve is the physical index for describing characteristics of a single lamp, although it is related to light distribution of the lighting environment constructed by multi-lamps. When light emits from a luminaire, direction of array is various. For LED lamp, package structure is designed to coordinate spatial distribution of array for specified light distribution. In the lighting environment of a single lamp, light intensity in different locations is likely to be described in polar or rectangular coordinate system. In this study, the lighting environment in the classroom is constructed by 11 lamps on the ceiling (2 transverse arrangement above the blackboard and 9 longitudinal direction in 3×3 arrangement). Light spatial distribution comes from the comprehensive effect of the 11 lamps. Equipped by lamps with different light distribution curves, light distribution in the classroom would be distinct.

TABLE 5. Significance test results of ocular parameters in the same illuminance between different lamps. ** represents significant difference with p<0.01.

Comparison pair	Significance Test
**Lamp1 & lamp2, ΔACC, 350lux	t=13.816, p=0
**Lamp1 & lamp2, ΔACC, 450lux	t=10.645, p=0
**Lamp1 & lamp2, ΔACC, 550lux	t=10.849, p=0
**Lamp1 & lamp2, ΔHOA4, 350lux	t=7.555, p=0
**Lamp1 & lamp2, ΔHOA4, 450lux	t=9.162, p=0
**Lamp1 & lamp2, ΔHOA4, 550lux	t=8.178, p=0
**Lamp1 & lamp2, ΔHOA12, 350lux	t=9.04, p=0
**Lamp1 & lamp2, ΔHOA12, 450lux	t=8.635, p=0
**Lamp1 & lamp2, ΔHOA12, 550lux	t=9.94, p=0

Compared to Sample 1 lamp, Sample 2 lamp presents much larger beam angle that is almost twice of Sample 1 lamp beam angle. Correspondingly, light intensity inside beam angle range of Sample 1's would be much larger than that of Sample 2 lamp. It is implied that light spatial distribution of Sample 2 lamp is much more even. In lighting environment with the same desk illuminance, ΔACC in Sample 1 lamp presents obviously higher than that in Sample 2 lamp (Figure 8A). Significance test is performed on ΔACC data, and results are shown in Table 5. It is indicated that accommodation ability of ciliary muscle is sensitive to light uniformity. In lighting environment with more even light distribution, ciliary muscle seems less likely to accumulate fatigue. Light spatial distribution causes more obvious ΔACC discrepancy than desk illuminance, and there is nearly no overlapping area between ΔACC error bars of the two kinds of lamps.

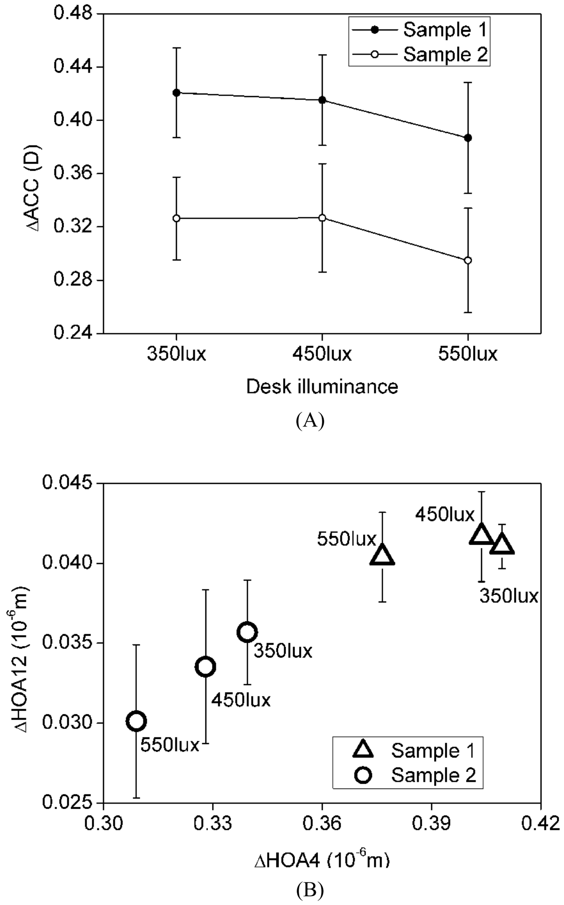


FIGURE 8. Comparison between different desk illuminances for (A) ΔACC in Sample 1 lamp, (B) ΔACC in Sample 2 lamp, (C) ΔHOA4 and ΔHOA12 in Sample 1 lamp and (D) ΔHOA4 and ΔHOA12 in Sample 2 lamp.

Light spatial distribution also has an obvious influence on ΔHOA4 and ΔHOA12 (Figure 8B). Significance test on ΔHOA data are also shown in Table 5. In lighting environment with more uniform light, variations of HOA4 and HOA12 would be less. Crystalline lens is an important assembly which plays the role of camera lens inside human eye imaging system. Crystalline lens changes its shape to obtain clear image in the retina, and the shape deformation is controlled by ciliary muscle tension. With the change of lighting environment, deformation tends to occur according to not only image in retina. According to our results, it seems that light spatial distribution triggers lens deformation more obviously compared to desk illuminance. When crystalline lens keeps in certain shape for long duration, it will be difficult for ciliary muscle to change the lens shape, and accommodation ability of ciliary muscle is likely to decrease, indicating that visual fatigue accumulation is obvious.

C. ACCOMMODATION MECHANISM

Vision is obtained by photon capture and signal conversion in retina, and signal transmission through nerve fibers. Signal conversion process occurs by photo-induced isomerization of 11-cis retinal. Image information in visual cortex is dependent on the number and wavelength of photons reaching retina. Without clear image formed in retina, the cortex will send signals through optical nerves to control ciliary muscles. Three kinds of nerve fibers play important roles in the ciliary accommodation process: sensory fibers, sympathetic fibers and parasympathetic fibers. Sensory fibers receive ocular perception and transmit to the cortex. Parasympathetic fibers control sphincter pupillae muscle and ciliary accommodation. Sympathetic fibers control pupil dilatator muscle. Increase and decrease of pupil size are controlled by different nerve fibers. In this study, PS values present rapid variations with light environment, since no significant differences are found between PS in different illuminances or different luminaires. It is inferred the parasympathetic fiber controlling pupil size is different from the one controlling ciliary accommodation.

IV. CONCLUSIONS

In the current study, physical indices influences of different luminaires on human eye are compared by variations of ocular physiological parameters. Physical indices of luminaire include desk illuminance of 350lux, 450lux and 550lux, and light distribution curve with average beam angle of 67.9 degrees and 116 degrees. Ocular physiological parameters include ACC, HOA4 and HOA12. These three parameters present similar trend in different desk illuminances and light distribution curves. In the lighting environment with desk illuminance of 550lux, variations of these three parameters (ΔACC, ΔHOA4 and ΔHOA12) reach the minimum values. When luminaire have light distribution curve with smaller average beam angle, the three parameters present larger variations. It is implied that accommodation ability of ciliary muscle inside human eye is influenced by both desk illuminance and luminance light distribution curve, and it is more sensitive to light distribution curve.

Desk illuminance is widely employed for light quality assessment in indoor lighting due to its effectiveness for light quality and convenience for measurement. However, it seems a little rough without taking user-desk distance and angle. Consequently, ocular physiological parameters in lighting environment with different desk illuminances present discrepancies that are not significant enough. Light distribution curve describes light distribution feature of luminaires, and it reflect light spatial distribution of lighting environment. It is implied that ocular physiological parameters are more sensitive to light spatial distribution compared to light quality. Physical indices of luminaires represent characteristics of emitted array. In this study, physical indices are related to ocular physiological parameters by influence during specified duration, and the relation is important for luminaire design and optimization. More researches are needed in the future for further insights into this relation.

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