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# Imaging Quality and Fatigue Quantification of Ocular Optical System

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**ABSTRACT** Human eye is a special kind of optical system, and its imaging quality and fatigue level seem susceptible to the illumination. In this study we were sought to develop a novel method to quantify ocular fatigue more accurately, and to assess the influence of light environment on ocular fatigue. Human factor experiments were performed on a total of 1249 participants. Among all physiological parameters, only accommodation and the 12th aberration presented significant variations during visual tasks. We deducted the ocular fatigue equation based on these two parameters together with other structural data. Regression equation and neural network were also constructed as complements. As a test, we predicted the ocular fatigue accumulations in various visual tasks. It was implied the predicted fatigue accumulations fell in separate ranges. It seems the novel method developed in this study could predict ocular fatigue accurately, and provide guidance to luminaire design.

**INDEX TERMS** Fatigue quantification, ocular optical system, visual task, light environment, predicted ocular fatigue.

## I. INTRODUCTION

Human eye is a special kind of optical system (Figure 1). Conventionally, an ordinary optical system (such as a camera) contains segments including aperture, lens, focus system and negative [1]–[3]. Aperture is used to control the entering-photon number [4]–[6], and its function is similar to the pupil [7]–[9]. Lens is used to change the array direction [10]–[12], and its function is quite similar to the combination of cornea [13]–[15] and crystalline lens [16]–[18]. Focus system in a camera is used for focal-distance adjustment, and its function is similar to the ciliary muscle. Negative is used to receive imaging, and it is similar to retina in human eye. However, an ordinary optical system is a simplified ocular optical system due to the lack of the self-adjustment function and inter-segment interactions. The concept of fatigue is not applicable for an ordinary optical system, as focal-distance adjustment is not performed by the optical system itself [19]–[21]. For an ocular optical system, however, fatigue is an important index to describe the system status.

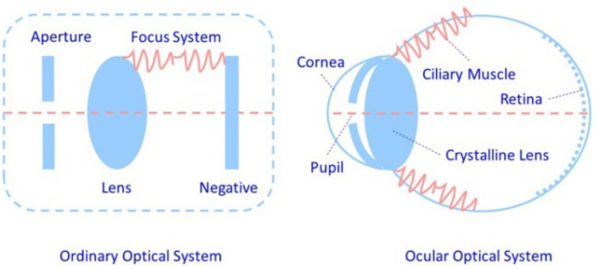


**FIGURE 1. Diagrammatic sketch on ordinary optical system and ocular optical system.**

Performance of an ordinary optical system is generally assessed by imaging quality [22]–[24]. Poor imaging tends to present low resolution with distortion. An ordinary optical system is unlikely to be influenced by imaging quality, since the characterization of each optical segment is constant. For a self-adjustment optical system (such as human eye), however, the influence of optical quality is not negligible, since the

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focal distance and other optical segments are adjusted according to the final imaging quality. For ocular system, the optical signal (imaging quality) is converted into neural signal, and transported to the visual cortex for information processing, and then the performance of the optical system is changed as the feedback due to neural modulation [25]–[27]. Optical system adjustment mainly relies on ciliary muscle fibers. With the stretching and contraction of ciliary fibers, ciliary muscle metabolism is increased, and fatigue is also likely to be accumulated. Consequently, ocular fatigue accumulation is dependent on the imaging quality.

Imaging quality is generally reflected by several physical characteristics, such as wave-front aberrations and spatial resolution. Wave-front aberrations are usually described by Zernike polynomial. Each Zernike term represents a segment of aberration [28]–[30]. Imaging quality is decreased due to aberrations resulting from image distortion, while spatial resolution affects imaging quality by blurring the inter-image boundaries. Although wave-front aberrations reduce imaging quality, each term of aberration is unlikely to be perceived by optic nerve of human eye. In addition to wave-front aberrations, imaging quality is also dependent on the structure of optical system. Consequently, the imaging quality of an optical system is likely to be described by the combination of wave-front aberrations, and system structure parameters. In this study, we were sought to assess fatigue accumulation of ocular optical system. Imaging quality parameter was investigated first based on wave-front aberrations, spatial resolution and system structural parameters (including KR and AL). Data were collected by human factor experiments.

## II. TESTING AND MEASUREMENT METHOD

As a special kind of optical system, human eye has similar structure to ordinary optical system. The structure contains aperture, lens, focus system and negative. For ocular optical system, the lens is characterized by KR (corneal refractive power), and focus system is similar to the parameter ACC (accommodation, which reflects the adjustment ability of ocular optical system) [31], [32]. AL (axial length) describes focus system in ocular optical system [33]–[35], and OA (ocular aberration) describes image distortion in the negative retina. In this study, the parameters KR, AL, ACC and OA were used to describe the imaging quality of ocular optical system.

To obtain KR, AL, ACC and OA, it is necessary to perform human factor experiments for data collection. Optical parameters of ocular optical system are changed to obtain the best-quality imaging. Consequently, imaging quality variation is more practical than imaging quality itself. In this study, we utilized visual tasks to cause variations. To cover various kinds of visual patterns, visual tasks were performed in three kinds of light environments: paper reading, screen watching and stereoscopic display. In this study, human factor experiments were performed on 1249 participants who were inspected and ensured without oculopathies such as cataracts, heterotropia, or amblyopia. Age distribution was in the range of 23∼35, with the average 30. Anisometropia was kept below 2.5D. Intraocular pressure distribute in the range of 14∼20. A majority of participants present the diopter in the range 1D ∼ −1D (40%) and the range −1D∼-3D (40%), with the rest in the range −3D∼ −5D (20%). Corrected visual acuity was 0.8 (40%) and 1.0 (60%). The ratio of male to female was 1:1. Among all the 1249 participants, ANN construction was based on 811 participants, and ANN verification was performed based on the other 438.

### A. ETHICS STATEMENT

The study (including the experimental protocols) was approved by the Standardization Administration of the People's Republic of China (SAC). All patients provided written informed consent. All methods were performed in accordance with the relevant guidelines and regulations.

### B. LIGHT ENVIRONMENT

In the human factor experiments for ANN construction, visual task pattern covers paper reading, screen watching, and stereoscopic display. These three patterns of visual tasks represent most ordinary uses of eye. In paper reading pattern, photons are emitted from the luminaire and knock the paper and table. Scattered photons enter human eye and interact with retina. In screen watching pattern, photons are emitted from the screen light source and enter the eye directly. In stereoscopic display, photons are emitted from two sources. Photons with slightly different phases enter two eyes.

In this paper, these three patterns of light environments were constructed in the same room (9m in length, 6m in width and 3m in height) in different days. For paper reading experiment, luminance of human eye location was set 200cd/m2, and correlated color temperature was set 5500K. The content of this visual task was Landolt rings counting. For screen watching experiment, luminance of human eye location was still set 200cd/m2 by the change of screen brightness. Correlated color temperature was also set 5500K. For stereoscopic display experiment, participants were equipped with 3D glasses. Luminance and correlated color temperature of stereoscopic display were set 200cd/m2 and 5500K respectively. The video for screen watching and stereoscopic display was chosen the movie "Moana" (IMDb code: tt3521164) in the format of mp4. Measurements were performed according to CIE 127:2007. Participant number of paper reading, screen watching and stereoscopic display was 303, 300 and 208 respectively (N = 811 in total).

Participants for verification (N = 438) executed another three the visual tasks: playground wandering, newspaper reading and VR (virtual reality) instrument watching. Human factor experiments consisted of playground wandering, paper reading and VR watching. The visual tasks of paper reading were newspaper reading in the environments of 550lux & 5500K, 550lux & 2700K, 200lux & 5500K and 200lux & 2700K respectively for 45min. VR task was "Moana"

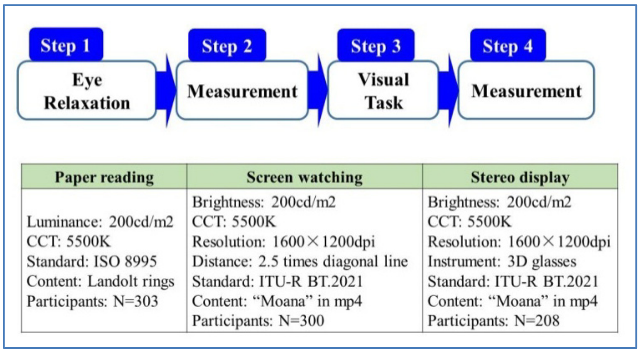


**FIGURE 2.** Detailed information of experimental process and environmental conditions during two-day experiments. For participants who present lasting migraine headaches, measurements were performed on them immediately as they quitted 3D movie watching.

(IMDb code: tt3521164) movie watching with the screen brightness of 200cd/m2 and the CCT of 5500K for 45min.

### C. HUMAN FACTOR EXPERIMENT

Human factor experiment consisted of four steps (Figure 2). First, each participant was told to look far into the distance for 15 min to reach an optimal and stable status. Second, measurements was performed on each participant to collect physiological parameter data including corneal refractive power (KR), axial length (AL), ciliary accommodation (ACC) and ocular aberrations (OA). Third, each participant was guided to execute the visual task. Fourth, the measurement was performed on each participant again to collect physiological parameter data including KR, AL, ACC and OA. Contents of the visual task cover paper reading, screen watching and stereoscopic display. Duration of each visual task was 90min.

KR and AL were measured by NIDEK AL Scan, and ocular aberrations were recorded using NIDEK OPD Scan III. During the measurement, each subject was asked to attach the forehead and chin to the specified location on the instrument, and glared at the target in the screen monocularly under natural condition. Ocular aberration data of the 1st∼35th Zernike terms were collected automatically by the instrument. Training trial was run for each subject before data collection until the task was well understood. The procedure was repeated after the training trial, and the collected data were in the form of Zernike expansions. Subjects were allowed to blink during the measurement to avoid aggravating of ocular fatigue caused by an extended inter-blink interval. Finally we used the 3rd∼14th terms aberrations.

Ciliary accommodation was collected by NIDEK AR−1*S*. Measurements were performed binocularly. Each subject was asked to attach the forehead and chin to the specified location on the instrument, and glared at the target in the screen binocularly under natural condition. Accommodation data were collected automatically by the instrument. Training trial was ran for each subject before data collection until the task was well understood. Subjects were not allowed to blink during the measurement to avoid the breaking of ciliary muscle status. All instruments used had been calibrated by The Measurement Test Research Institute of Beijing. Experiments for ANN verification were similar.

**TABLE 1.** Significance test of participants in paper reading, screen watching and stereoscopic display.

| Comparison | N | Mean Age | t | p |
|---|---|---|---|---|
| Paper & Screen | 303 | 31 | 0.92 | 0.36 |
| Paper & Stereoscopic | 300 | 28 | -12.18 | 0 |
| Screen & Stereoscopic | 208 | 28 | -12.07 | 0 |

## III. RESULTS AND DISCUSSION

Human eye is a sophisticated and precise instrument with self-adjustment. Ocular structure is quite similar to a camera, which contains lens (cornea and crystalline lens), shutter and aperture (pupil), film (retina) and body (vitreum). Ciliary muscle fibers in human eye stretch the crystalline lens and make it deformed, thus changing the image quality in retina. During this process, values of ACC and OA change while KR and AL remain constant. Variations of ACC and OA reflect the status of human eye. ACC describes ciliary muscle accommodation, which reflects fiber adjusting ability. Ciliary accommodation contains two important parts: near point accommodation (ciliary muscle fibers adjust the crystalline lens from the current status to the tensest status) and far point accommodation (ciliary muscle fibers adjust from the current status to the completely loose status). In this work, we used far point accommodation to investigate ACC variation regularity. OA data were collected from the 3rd to the 14th terms of Zernike polynomials.

Human factor experiments were performed on participants of paper reading and screen watching to collect data including ACC and OA. Values of $\Delta$ACC and $\Delta$OA could reflect the influence of visual task on optical elements. Significance test was performed on $\Delta$ACC for participants between paper reading and screen watching, and no significant difference was found between participants in these two patterns of light environments, while significance exists between paper reading/screen watching and stereoscopic display (Table 1).

For ocular aberrations ($\Delta$OA), comparisons were made on participants between paper reading and screen watching, between paper reading and stereoscopic display, and between screen watching and stereoscopic display (Figure 2A∼2L). For variations of the 3rd term aberrations ($\Delta$OA3), the medians in paper reading and screen watching present higher than the median in stereoscopic display, but the differences were not significant ($t = 0.98$ and $p = 0.33$ between paper reading and stereoscopic display, and $t = 1.67$ and $p = 0.1$ between screen watching and stereoscopic display). For OA4, differences between medians were quite tiny without significances ($t = 1.78$ and $p = 0.08$ between paper reading and stereoscopic display, and $t = 0.98$ and $p = 0.33$ between screen watching and stereoscopic display). For $\Delta$OA5, participants in paper reading and screen watching present higher medians than those in stereoscopic display although without significances (t = 1.43 and p = 0.16 between paper reading and stereoscopic display, and t = 1.33 and p = 0.19 between screen watching and stereoscopic display). For ΔOA6, participants in paper reading present lower median than stereoscopic display participants, while participants in screen watching present quite similar to stereoscopic display participants, but there were no significances (t = −1.15 and p = 0.25 between paper reading and stereoscopic display, and t = −0.23 and p = 0.82 between screen watching and stereoscopic display). For ΔOA7, participants in the three types of light environments present similar without significant differences (t = −0.23 and p = 0.82 between paper reading and stereoscopic display, and t = −0.06 and p = 0.95 between screen watching and stereoscopic display). For ΔOA8, participants in paper reading and stereoscopic display present quite similar medians, while screen watching participants present higher medians, but there were no significant differences (t = −0.45 and p = 0.65 between paper reading and stereoscopic display, and t = 0.15 and p = 0.88 between screen watching and stereoscopic display). For ΔOA9, participants in paper reading and screen watching present higher medians than those in stereoscopic display, but the differences were not significant (t = 0.22 and p = 0.83 between paper reading and stereoscopic display, and t = 0.02 and p = 0.98 between screen watching and stereoscopic display). For ΔOA10 (t = −0.92 and p = 0.36 between paper reading and stereoscopic display, and t = 0.22 and p = 0.82 between screen watching and stereoscopic display) and ΔOA11 (t = −0.99 and p = 0.32 between paper reading and stereoscopic display, and t = 0.65 and p = 0.52 between screen watching and stereoscopic display), participants in the three types of light environments were similar without significant differences. For ΔOA12, significant differences were found in participants between paper reading and stereoscopic display (t = 2.38, p = 0.02), and between screen watching and stereoscopic display (t = 1.26, p = 0.02). For ΔOA13 and ΔOA14, participants in paper reading and screen watching present higher medians than stereoscopic display participants, but without significances (t = 0.23 and p = 0.82 between paper reading and stereoscopic display, and t = 0.53 and p = 0.59 between screen watching and stereoscopic display).

Compared to ΔACC, variation of OA presents irregular in different light environments except for the 12th term OA with significant difference (t = 2.38 and p = 0.02 between paper reading and stereoscopic display, and t = 1.26 and p = 0.02 between screen watching and stereoscopic display). ACC is quite sensitive to light environment, and it is appropriate to reflect ocular physiological variations accompanied to ocular discomfort or fatigue. This is because ACC directly describe the adjustment (contraction and relaxation) of ciliary muscle fibers. With the process of ciliary adjustment (accommodation), fibers stretch the crystalline lens and lead to its deformation. As curvature variation of the anterior and the posterior surface, OA value is likely to change. According to Zernike polynomials, OA could be resolved into many Zernike terms. Ciliary accommodation may lead to variation of OA, but variation is likely to be irregular for a certain Zernike term.

### A. IMAGING QUALITY

Aberration has been used in imaging quality assessment for years, as it is related to image resolution. However, there are many terms of Zernike aberration terms that describe different aspects of image distortions, and not all Zernike terms are likely to be perceived. In addition, aberrations in various terms make different contributions to the final imaging quality. MTF (Modulation Transfer Function) is an ideal parameter to describe the imaging quality of the optical system, but it is a comprehensive parameter contributed by various terms of aberrations. According to the above results, only the 12th term aberrations present significant difference between paper reading/screen watching participants and stereoscopic display participants. The variation results from the influence of visual task (light environment), therefore the imaging functions are likely to present disparity among different participants. Consequently, in this study the 12th term aberration was employed to describe the imaging disparity between participants in different light environments. Visual quality index could be calculated from the 12th term aberration value based on the pupil function:

$$\mathrm{P}(\mathrm{x}, \mathrm{y}) = \mathrm{p}(\mathrm{x}, \mathrm{y}) \cdot \exp(\mathrm{iW}(\mathrm{x}, \mathrm{y})) \tag{1}$$

W is the aberration of human eye:

$$W_k(\rho, \theta) = \sum\nolimits_k C_k Z_k(\rho, \theta) \tag{2}$$

In the equation above, P is the pupil function, and W is the aberration of human eye. In this study, only the 12th term aberration was used since other terms presented differences without significance. The value of ocular aberration in retina tends to be amplified or contracted due to the imaging distance and cornea curvature. With the conversion from rectangular coordinate system to polar coordinate system, the equation could be recorded as follows:

$$\mathrm{P}(\rho, \theta) = \mathrm{p}(\rho, \theta) \cdot \exp\left(i \cdot \frac{c_{12} Z_{12}(\rho, \theta)}{\mathrm{AL} \cdot \mathrm{KR}}\right) \tag{3}$$

$$\mathrm{p}(\rho, \theta) = \frac{1}{\pi}(\rho \leq 1) \tag{4}$$

$$Z_{12}(\rho, \theta) = 6\rho^4 - 6\rho^2 + 1 \tag{5}$$

Imaging quality density is represented by q here

$$\mathrm{q}(\rho, \theta) = \iint P(\rho', \theta') \cdot P^*(\rho' - \rho, \theta' - \theta)\rho' d\rho' d\theta' \tag{6}$$

In the integration, the range of $\theta$ is [0,2$\pi$] and the range of $\rho$' is (0, 1) due to normalization. By calculation it was

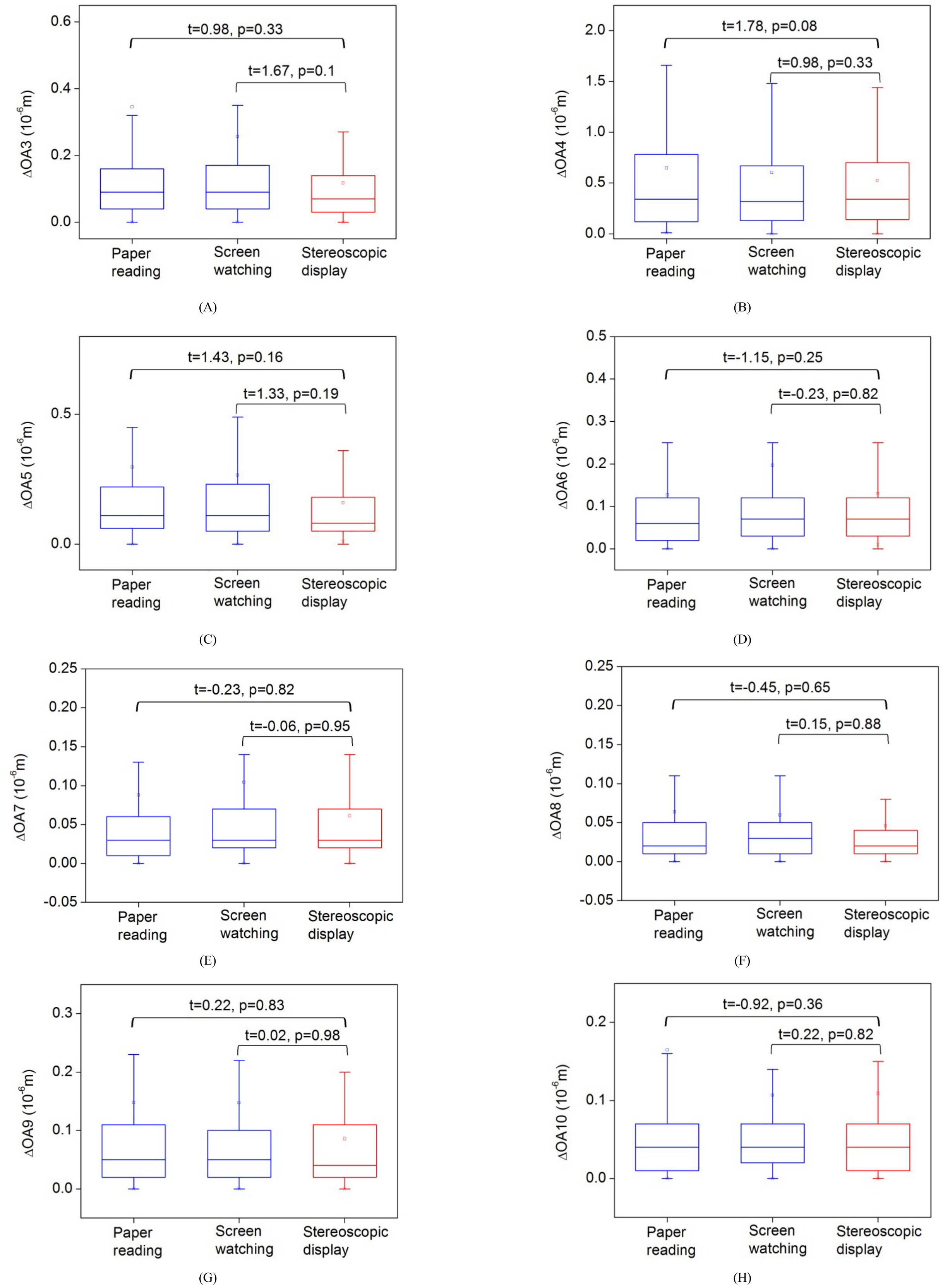


**FIGURE 3. Comparison of ΔOA between participants in paper reading, screen watching and stereoscopic display. Horizontal axis represent light environments, and vertical axis represents aberration terms. (A) ΔOA3; (B) ΔOA4; (C) ΔOA5; (D) ΔOA6; (E) ΔOA7; (F) ΔOA8; (G) ΔOA9; (H) ΔOA10; (I) ΔOA11; (J) ΔOA12; (K) ΔOA13; (L) ΔOA14.**

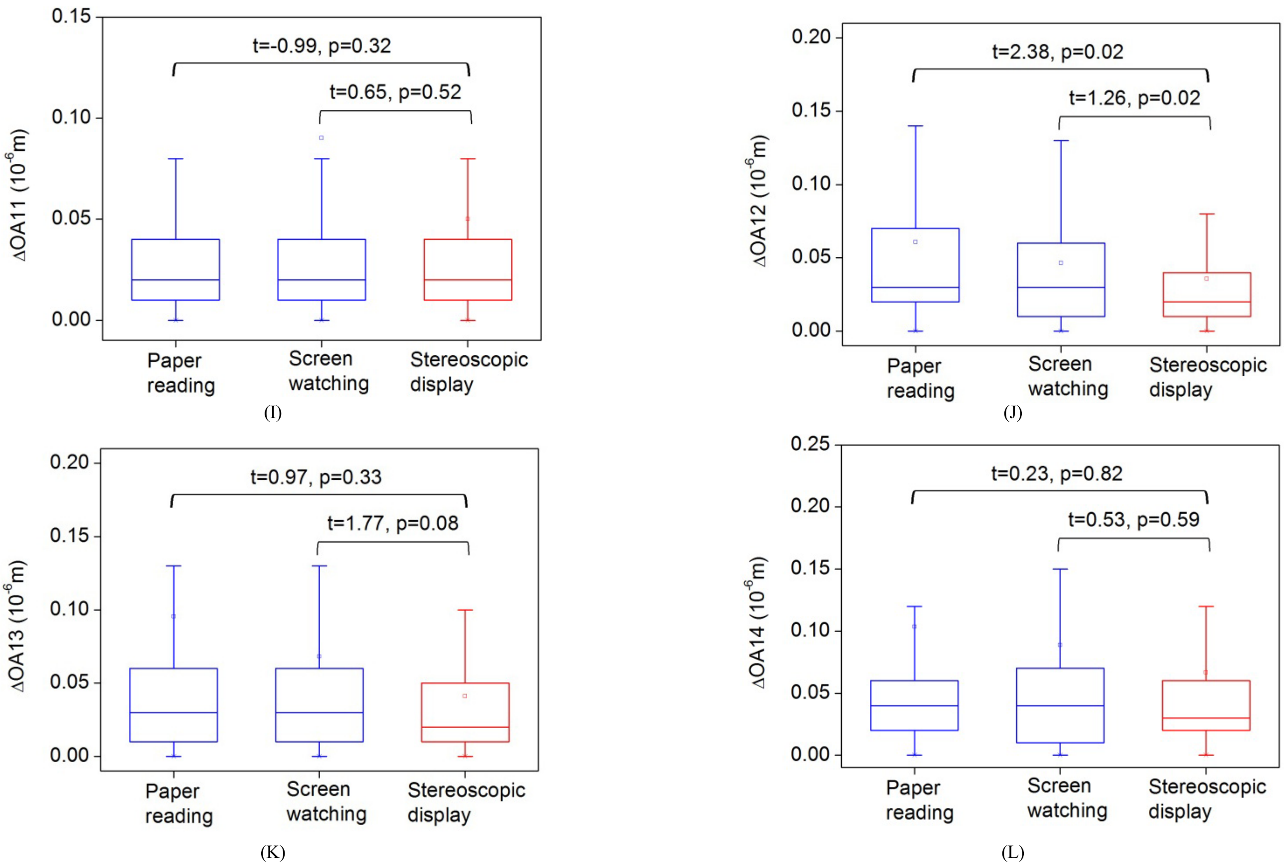


**FIGURE 3.** ***(Continued.)*** **Comparison of ΔOA between participants in paper reading, screen watching and stereoscopic display. Horizontal axis represent light environments, and vertical axis represents aberration terms. (A) ΔOA3; (B) ΔOA4; (C) ΔOA5; (D) ΔOA6; (E) ΔOA7; (F) ΔOA8; (G) ΔOA9; (H) ΔOA10; (I) ΔOA11; (J) ΔOA12; (K) ΔOA13; (L) ΔOA14.**

obtained that

$$q(\rho) = \frac{2}{\pi}\exp\left(\mathrm{i}\cdot\frac{c_{12}}{\mathrm{AL}\cdot\mathrm{KR}}\cdot 6(\rho^2-\rho^4)\right) \cdot\int \exp(\mathrm{i}\cdot\frac{c_{12}}{\mathrm{AL}\cdot\mathrm{KR}}\cdot 12\rho'\rho(2\rho'^{2-3\rho'}\rho+2\rho^2-1))\mathrm{d}\rho' \tag{7}$$

The integration above is complex and could not be calculated directly. Given that the value of $\rho$ is tiny, it could be simplified by approximating

$$q(\rho) \approx \frac{2}{\pi}\exp\left(\mathrm{i}\cdot\frac{c_{12}}{\mathrm{AL}\cdot\mathrm{KR}}\cdot 6(\rho^2-\rho^4)\right) \cdot\int\left(1+\mathrm{i}\cdot\frac{c_{12}}{\mathrm{AL}\cdot\mathrm{KR}} \cdot 12\rho(2\rho'^{3-3\rho'^2}\rho+2\rho'\rho^2-\rho')\right)\mathrm{d}\rho' \tag{8}$$

By calculation the imaging quality density q could be obtained as

$$q(\rho) = \frac{2}{\pi}\exp\left(\mathrm{i}\cdot\frac{c_{12}}{\mathrm{AL}\cdot\mathrm{KR}}\cdot 6(\rho^2-\rho^4)\right) \cdot(1+\mathrm{i}\cdot\frac{c_{12}}{\mathrm{AL}\cdot\mathrm{KR}}\cdot 12\rho^2(\rho-1)) \tag{9}$$

The expression of imaging quality Q' is the integration in the range of [0,1], so finally it was obtained

$$\mathrm{Q}' = \int q^* q\, d\rho = \frac{4}{\pi^2}\cdot[1-\left(\frac{12\cdot c_{12}}{AL\cdot KR}\right)^2] \tag{10}$$

The variable c12 equals to the value of OA12 for the corresponding participant. For simplicity, only the term with variables was contained for the final expression of imaging quality Q

$$\mathrm{Q} = \left(\frac{10000\cdot c_{12}}{AL\cdot KR}\right)^2 \tag{11}$$

The unit was ignored with only values contained for calculation. Ocular fatigue is generally perceived as poor imaging quality and decreased function of ciliary muscle fibers. For fatigue quantification of the ocular optical system, in this study we treated ocular fatigue (OF) as the binary function of imaging quality Q and ciliary accommodation ACC:

$$\mathrm{OF} = \mathrm{OF}(\Delta\mathrm{Q}, \Delta\mathrm{ACC}) \tag{12}$$

Boundary condition is necessary for the quantification of OF. In this study, we were sought to classify OF in the range of 0~1: 0 representing no fatigue), and 5 representing unendurable fatigue. According to the quantification of OF, we could get the minimum value of OF (OF = 0) with $\Delta Q = 0$ and/or $\Delta ACC = 0$. The maximum value of OF (OF = 1) corresponds to the participants presenting severe lasting migraine headache.

### B. BP-ANN ANALYSIS

BP-ANN analysis is a kind of supervised learning neural network which is widely used technique. It searches for small approximation by the steepest gradient descent method. There are three layers in BP-ANN structure: input layer, hidden layer, and output layer. Each two adjacent layers are connected directly. Connection is described by different weights. For the hidden layer, the outputs are as follows:

$$\mathrm{net}_j = \sum\nolimits_{i=0}^{n} v_{ij} x_i \quad j = 1, 2, \cdots, m \tag{13}$$

$$\mathrm{y}_j = f_H(net_j) \quad j = 1, 2, \cdots, m \tag{14}$$

In the equations, netj is the activation value of the jth node, yj is the output of the hidden layer, and fH is the activation function of a node:

$$f_H(x) = \frac{1}{1 + \exp(-x)} \quad j = 1, 2, \cdots, m \tag{15}$$

For the output layer, the outputs of neurons are described as

$$O = f_O(\sum\nolimits_{j=0}^{m} w_{jk} y_j) \quad j = 1, 2, \cdots, m \tag{16}$$

where fO is the activation function. Values of w are randomly assigned initially, and then modified based on the delta rule. For the construction of BP-ANN it is necessary to confirm the input layer and the output layer. In this study, the input layer included the ΔQ and ΔACC, and the output layer the number in the range of 0∼1. For each participant, the input layer (ΔQ and ΔACC) could be obtained by data collection from human factor measurements, while the output layer could not be confirmed directly. Only those participants presenting little physiological variation could be designated OF = 0, and those presenting severe migraine headache could be designated OF = 1. According to the ΔQ, ΔACC and OF values of these two kinds of participants, we constructed a calculation equation by regression, and calculated the OF values of the rest participants. In this study, there were 28 participants used for equation regression: 12 participants were designated OF = 0 (Q orders distribute in the range of 10-7∼10-5), and 16 participants were designated OF = 1 (Q values distribute in the range of 5∼38). The equation was

$$\mathrm{OF} = 0.07 \ln(\Delta Q) + 0.02\sqrt{\Delta ACC} + 0.77 \tag{17}$$

The ANOVA of the fitting indicates that F = 389.9, p = 0. The value of R2 in the fitting is 0.98. By the above equation, OF values of all participants were calculated. Most OF values calculated fell in the range 0∼1, although 5 of them were below 0 and 4 of them were above 1.

We chose those calculated numbers in the range of 0∼1 as the input layer to construct the network (802 participants in total for ANN construction, after deleting the 5 with OF<0 and the 4 with OF>1). The training set were chosen 90% of all data and the test set were 10%. The network was then constructed with the confidence level of 0.898. It was implied that the network constructed in this study could well predict the fatigue level (Figure 4).

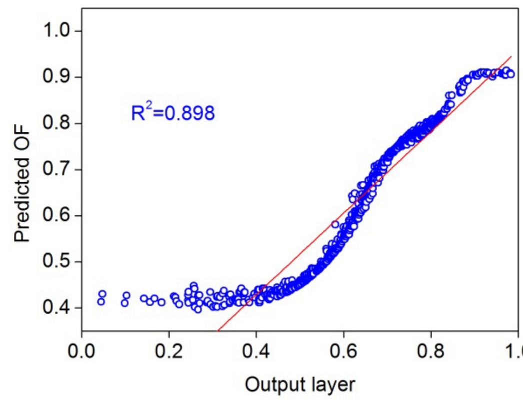


**FIGURE 4.** Calculated OF values by the constructed BP-ANN. The horizontal axis represents the output layer used to construct the BP-ANN, and the vertical axis represents the calculated OF values by the constructed network.

### C. ACCURACY TEST

To verify the application of our ocular fatigue assessment method, human factor measurements were performed on another 438 participants. Among these participants, 71 went to the playground to walk around for 45min, 296 were seated in the classroom and read newspapers for 45min (71 in the environment of 550lux & 5500K, 74 in the environment of 550lux & 2700K, 73 in the environment of 200lux & 5500K, and 78 in the environment of 200lux, 2700K), and the other 71 were equipped with VR instruments and watched VR movie (with the screen brightness of 200cd/m2 and the correlated color temperature of 6000K) for 45min. Prior to and following the visual tasks, data of KR, AL, OA12 and ACC were collected for each participant. Then OF value of each participant was calculated based on the BP-ANN constructed above, and OF distribution was shown in Figure 5. OF values distribute in the range of 0∼1. Participants of playground wandering presented OF values distributing mainly in the range of 0.38∼0.45. For newspaper-reading participants, OF values covered the range 0.4∼0.7, and VR users presented OF values almost above 0.8. Although with overlapping areas, OF values of the three kinds of participants were almost separated.

There was nearly no eye-use in the task of walking around in the playground, so ocular fatigue accumulation was likely to be the least in playground-wandering task. Most participants in this task presented the OF value around 0.42. The OF range 0.38∼0.45 was far above 0. This may imply that ocular fatigue difference from OF = 0 to OF = 0.4 is not obvious. According to OF distribution of newspaper-reading tasks, participant frequency in each environment was separated obviously although with

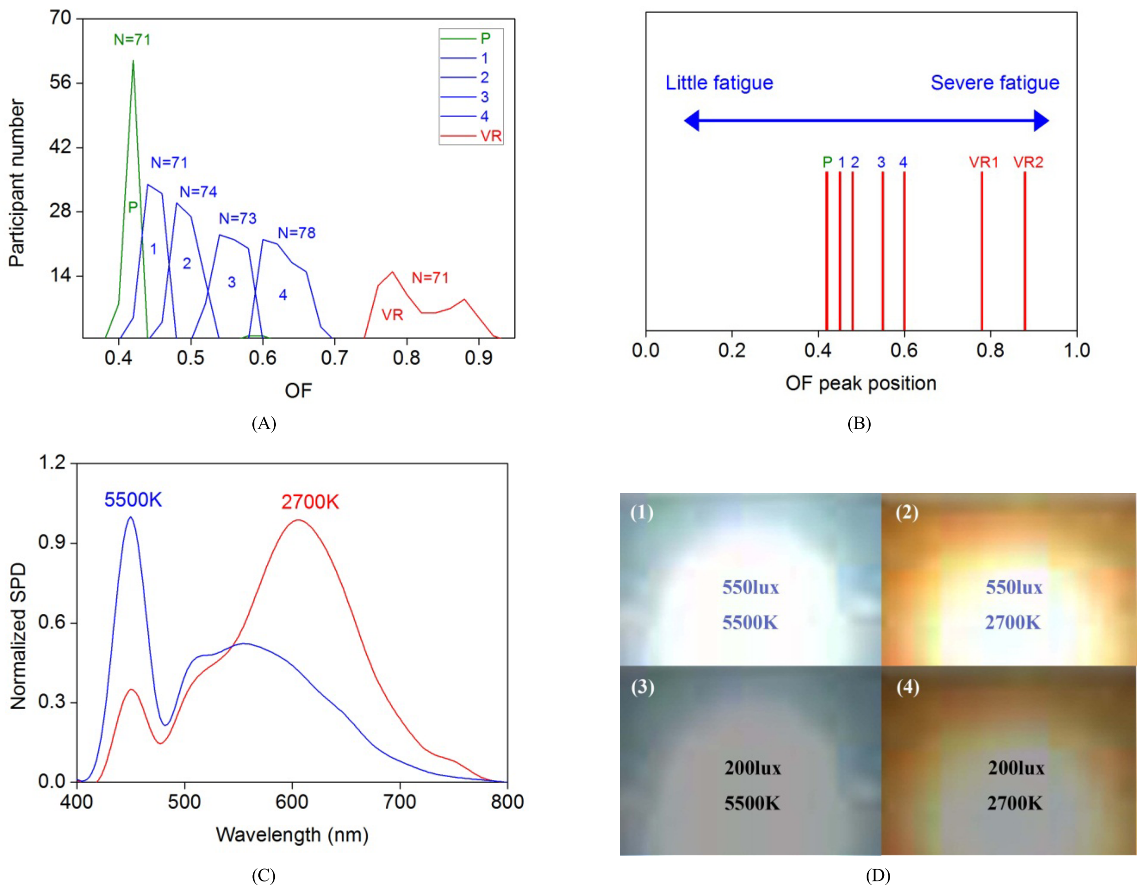


**FIGURE 5.** OF distribution of participants in playground, classroom and VR. (A) Frequency distribution; P represents playground walking; 1 represents newspaper reading in 550lux&5500K; 2 represents newspaper reading in 550lux&2700K; 3 represents newspaper reading in 200lux&5500K; 4 represents newspaper reading in 200lux&2700K; VR represents VR watching. (B) OF peak position in the predicted OF axis. (C) SPD of the CCT 2700K and 6000K. (D) Luminaires of the four light environments for newspaper reading; 1 represents newspaper reading in 550lux&5500K; 2 represents newspaper reading in 550lux&2700K; 3 represents newspaper reading in 200lux&5500K; 4 represents newspaper reading in 200lux&2700K.

overlapping areas. Previous studies indicated that appropriate desk illuminance was around 550lux while the proper CCT was near 5500K [36]. From Figure 5A, it was suggested that the 550lux&5000K group presented the least OF values among the four newspaper-reading groups, and the 200lux&2700K presented the highest OF values due to the large difference from the appropriate illuminance and the proper CCT.

In the light environment with desk illuminance above 200lux, photopic vision dominates the vision function. Cone cells in retina receive photons and transform optical signal into neural signal. With low desk illuminance, part of cone cells are activated while more receive no enough photons [37]–[39]. In this situation, ciliary muscle adjusts pupil size and crystalline lens to get higher quality imaging. Consequently, ocular fatigue is more likely to be accumulated due to the excessive use of eyes. Imaging in retina is generally in multiple colors. Cone cells in retina are sensitive to different kinds of colors and could be divided into three parts: blue cones (with the peak wavelength around 450nm), green cones (with the peak wavelength around 550nm) and red cones (with the peak wavelength around 580nm). The LED luminaire in 5500K covers most wavelengths in the range of cone cell sensitivity, while the 2700K contains only the red part (Figure 5C and 5D). This may lead to the perception difference of vision.

Regarding the four newspaper-reading groups, the peak position of the distribution shape was nearly 0.45, 0.48, 0.55 and 0.6 respectively. VR employment was likely to lay more influence on human eye compared to newspaper-reading tasks, and the corresponding OF values were also in consistence. VR participants presented the OF distribution with double peaks (OF = 0.78 and OF = 0.88 respectively), indicating two types of participants with and without obvious migraine headache respectively. OF peak position could represent the overall OF characterization of the group in certain light environment. The OF peak position was shown in Figure 5B for the six groups in this study. According to the OF definition, OF = 0 represents the status with little ocular physiological variation, and OF = 5 corresponds to the status with severe migraine headache. In Figure 5B, the words ''little fatigue'' and ''severe fatigue'' was not based on subjective perception, but to describe the fatigue degree based on ocular physiological variations.

From the OF peak position, it was implied that OF values of participants in this study mainly distributed in the range of 0.4∼0.9, with an obvious gap in the range 0∼0.4. According the definition, OF = 0 represents an ideal status without fatigue, while OF = 0.4 represents the calculated status little fatigue. Difference between OF = 0 and OF = 0.4 should not be obvious. Red vertical lines in Figure 5B divided the whole range 0∼1 into several levels representing various fatigue degrees. The relative OF position reflected different fatigue levels, but the distances in the horizontal axis did not distribute evenly and could not reflect fatigue variations. To classify the fatigue degree into separated levels, we could refer to the OF distribution of participants rather than OF values.

Previous assessments on ocular fatigue or discomfort were mainly based on subjective perception, which lacks accuracy and stability due to the influence of cognition and emotion. In this study, we proposed an objective method for quantitative assessment on ocular fatigue. According to the OF distribution of participants in various light environments, we could obtain the influence of the corresponding environment on human eye. This is important for the assessment of luminaire and light environment, and is applicable in the field of luminaire design. By the method proposed in this study, the effect and performance of OF classification result relies on sample capacity. With the increase of the participant number, the classification of OF distribution would be more clear and fine.

## IV. CONCLUSION

Human eye is a self-adjusting optical system. Compared to ordinary optical system, human eye presents more complicated since the self-adjusting feature is likely to cause fatigue. Ocular fatigue of human eye is characterized by decreased accommodation ability and poor imaging quality. The subjective perception of ocular fatigue tends to be interfered with emotion and cognition, so we were sought to assess and classify the fatigue level objectively by fatigue responses of physiological parameters. Human factor experiments were performed to collect physiological data including KR, AL, OA12 and ACC. The quantification is designed to be 0 representing no fatigue and 1 representing unendurable fatigue. The feature of each level is subjectively descriptive, but our fatigue quantification originated from physiological parameters and avoided subjective description. All data were collected by instruments. This study opened a novel method for quantification by objective variations of ocular physiological parameters.

In this study, we combined equation regression and BP-ANN methods to figure out the relation between ocular physiological parameters (KR, AL, ACC, OA12) and fatigue level (0∼1). There was no reference as the output layer, so we chose two extreme conditions as the boundary condition: participants presenting little physiological variation were designated OF = 0 (N = 12), while participants presenting severe migraine headache were designated OF = 1 (N = 16). Based on these conditions, we constructed the equation by regression, and calculated more OF values. According to these more OF values, the final BP network was constructed (N = 802, except for 5 with OF<0 and 4 with OF>1). It is implied that the network is credible since R2 of the equation is 0.98 and confidence level of the network is 0.898. OF values of participants executing various visual tasks fell in separate groups in the range of 0∼1 (N = 216), indicating that our BP-ANN is applicable for quantitative assessment. In this study, the regression and the network was reliable due to the large participant number.

The assessment method proposed in this study is likely to be applicable in the field of luminaire design. There have been standards stipulating optical performance of luminaires such as illuminance, CCT (correlated color temperature), SPD (spectral power distribution). However, the stipulations were not always based on quantitative assessment methods, since most assessments on ocular fatigue were subjective. This study provides an objective quantitative method for ocular assessment, making it possible to assess ocular fatigue more accurate. Participants of various visual tasks presented different OF distributions, suggesting that ocular fatigue could be classified into several levels representing different fatigue degrees. Each level of visual fatigue is likely to be caused by certain optical performances. The connection between luminaire optical performance and ocular fatigue level is quite important for luminaire design, although the connection has not been constructed. More experiments are needed for further insights.

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