

Objective Evaluation of Visual Fatigue Using Binocular Fusion Maintenance

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Received: 29 May 2017

Accepted: 24 January 2018

Published: 23 March 2018

Keywords: Binocular vision; binocular fusion; visual fatigue; eye movement

Citation: Hirota M, Morimoto T, Kanda H, Endo T, Miyoshi T, Miyagawa S, Hirohara Y, Yamaguchi T, Saika M, Fujikado T. Objective evaluation of visual fatigue using binocular fusion maintenance. *Trans Vis Sci Tech.* 2018;7(2):9, <https://doi.org/10.1167/tvst.7.2.9>

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Purpose: In this study, we investigated whether an individual's visual fatigue can be evaluated objectively and quantitatively from their ability to maintain binocular fusion.

Methods: Binocular fusion maintenance (BFM) was measured using a custom-made binocular open-view Shack–Hartmann wavefront aberrometer equipped with liquid crystal shutters, wherein eye movements and wavefront aberrations were measured simultaneously. Transmittance in the liquid crystal shutter in front of the subject's nondominant eye was reduced linearly, and BFM was determined from the transmittance at the point when binocular fusion was broken and vergence eye movement was induced. In total, 40 healthy subjects underwent the BFM test and completed a questionnaire regarding subjective symptoms before and after a visual task lasting 30 minutes.

Results: BFM was significantly reduced after the visual task ($P < 0.001$) and was negatively correlated with the total subjective eye symptom score (adjusted $R^2 = 0.752$, $P < 0.001$). Furthermore, the diagnostic accuracy for visual fatigue was significantly higher in BFM than in the conventional test results (aggregated fusional vergence range, near point of convergence, and the high-frequency component of accommodative microfluctuations; $P = 0.007$).

Conclusions: These results suggest that BFM can be used as an indicator for evaluating visual fatigue.

Translational Relevance: BFM can be used to evaluate the visual fatigue caused by the new visual devices, such as head-mount display, objectively.

Introduction

Visual fatigue is increasing in prevalence with the widespread use of computers and smartphones.^{1–6} It is normally diagnosed by physicians from the patients' subjective symptoms because objective assessments have not yet been established.^{5,7–9} However, visual fatigue may be present before the subject is able to identify any symptoms. Especially, there is a clear and urgent need for an objective method for the early diagnosis of visual fatigue in pilots, athletes, or

some other group of individuals for whom stamina in binocular vision is vitally important because visual fatigue can lead to fatal failure.

Vergence is the simultaneous opposite eye movements to obtain or maintain binocular vision, and accommodation is the process for varying its refractive power to produce a focused image on the retina for different object distance. Normal binocular vision comprises vergence and accommodation systems that act simultaneously.¹⁰ Because visual fatigue can result from vergence–accommodation conflict,^{11,12} previous studies have investigated ways to evaluate visual

fatigue objectively from vergence and accommodation parameters, such as fusional vergence range, near point of convergence (NPC), and high-frequency component (HFC) in microfluctuations of accommodation.^{13–16} However, there have been problems with reproducibility for both vergence^{13–15} and accommodation.^{17,18}

Diplopia is the subjective complaint of seeing two retinal images of the single object and is one of the most prevalent visual symptoms associated with visual fatigue in nonstrabismic computer workers.¹⁹ This is caused by the deviation of one eye to heterophoric posture (eso- or exo- deviation) when sensory and motor fusion are diminished²⁰; therefore, the ability to maintain binocular fusion, which merges two retinal images in the brain,²¹ may be an objective parameter to represent visual fatigue.

Binocular fusion maintenance (BFM) can be assessed by reducing the intensity of incident light on one eye, which is defined by the number of photons, because the perceptive size of retinal image depends on the intensity of incident light.²² Moreover, the binocular fusion break can be judged automatically to record the eye movements.²³ However, the conventional fusion test of red-filter ladder²⁴ does not reduce the intensity of incident light on the eye in a linear manner.²⁵

Therefore, we have developed a binocular wavefront sensor equipped with a variable liquid crystal shutter with which the intensity of incident light on the eye can be reduced linearly. BFM can be evaluated from the transmittance of the liquid crystal shutter at the point when binocular fusion breaks and one eye deviates to a heterophoric position.

The purpose of this study was to investigate whether BFM, as evaluated by the transmittance of the liquid crystal shutter, represents visual fatigue following a visual task.

Methods

Subjects

Forty-four volunteers participated in this study. All were volunteers and each underwent an ophthalmologic examination that included the definition of ocular dominance using the near hole-in-card test, visual acuity at distance (5.0 m), amplitude of accommodation (ARK-1s; Nidek Co. Ltd., Aichi, Japan), stereo acuity (Titmus Stereo Tests; Stereo Optical Co., Inc, Chicago, IL), and angle of deviation using the alternate prism cover test both

near (33 cm) and at distance (5.0 m). Stereo acuity was converted to logarithm of arcsecond (log arcsec).

Potential subjects were excluded if they had manifest strabismus or nystagmus. People with near orthophoria were also excluded because, in these cases, the nondominant eye would not deviate even when binocular fusion was broken, preventing the measurement of BFM.

The nature and possible complications of the study were explained to all the subjects and each gave written informed consent. This investigation adhered to the tenets of the World Medical Association Declaration of Helsinki. The experimental protocol and consent procedures were approved by the institutional review board of Osaka University Medical School (15294-4).

Measurement of Binocular Fusion Maintenance

Apparatus

BFM was measured using a custom-made binocular, open-view Shack–Hartmann wavefront aberrometer (Fig. 1a; Binocular open-view Shack–Hartmann wavefront sensor [BWFA]; Topcon Corp., Tokyo, Japan) with 840-nm infrared light.^{26,27} The BWFA was equipped with an eye tracker system that was used to monitor the pupil and corneal reflection with 940-nm infrared light. This instrument measured and recorded binocular eye movement, wavefront aberrations, and pupil size simultaneously, at a sampling rate of 30 Hz.

Variable liquid crystal shutters (X-FOS (G2)-CE 2×2; LC-Tec Displays AB, Borlänge, Sweden) were placed between the BWFA and the eyes of the subject (Fig. 1b). The transmittance of the liquid crystal shutter was linearly changed from 0.07% to 23.0%, that was averaged in the wavelengths between 430 and 720 nm, confirmed using a spectroradiometer (SR-LEDW; Topcon Corp.).

Calibration of Eye Movements

During calibration, the subject was asked to fixate on eight horizontal asterisk targets on a calibration plate placed 50 cm in front of their eyes. The positions of these targets in the horizontal plane were -8.0° , -5.7° , -3.4° , -1.1° , $+1.1^\circ$, $+3.4^\circ$, $+5.7^\circ$, and $+8.0^\circ$. Using a calibration curve, the distance between the center of the pupil and the corneal reflection was translated into the angle of ocular rotation. The measurement error at 50 cm was 0.3° to 0.5° (interquartile range).

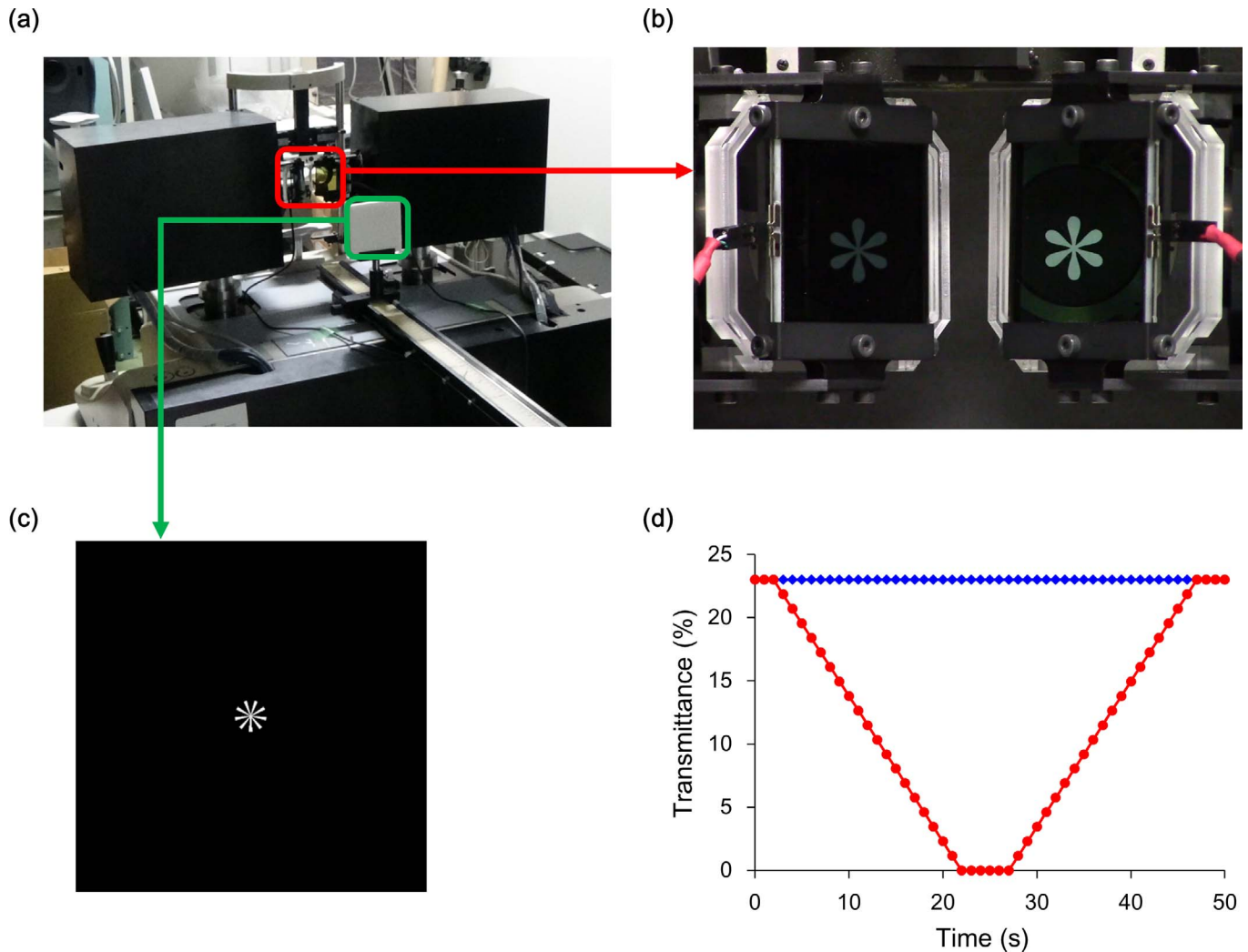


Figure 1. Apparatus for measuring binocular fusion maintenance. (a) Binocular open-view Shack-Hartmann wavefront sensor. (b) Liquid crystal shutter. (c) Fixation target. The starburst target was set at 33.3 arc minutes of visual angle. (d) Transmittance during the binocular fusion maintenance test for the dominant and nondominant eyes (*blue* and *red*, respectively). Transmittance did not change for the dominant eye.

Procedure for Measuring BFM

The subject's spherical and cylindrical errors were corrected using objective values obtained from the BWFA at 5.0 m. An examiner asked the subject about the sharpness of the target (Fig. 1c) and added plus lenses to both eyes equally until the target could be seen clearly. This confirmed that the subject's binocular visual acuity at 33 cm was equal to or better than 0.1 logMAR.

The subject's eye position, wavefront aberrations, and pupil diameter were measured and recorded continuously for 50 seconds at 270 lx (Supplementary Movie S1) using a luminometer (LM-331; AS ONE Corp., Osaka, Japan). The transmittance of the liquid crystal shutter for the nondominant eye, which was

determined by the hole-in-card test, was set at 23.0% for 2 seconds and then reduced sequentially by 1.15% every second (Fig. 1d); it was then maintained at 0.07% between 22 and 27 seconds. The transmittance was then increased by 1.15% every second and finally maintained at 23.0% between 47 and 50 second. Transmittance for the dominant eye was sustained at 23.0% throughout the 50-second period.

The BFM test was performed three times before and three times after the visual task. There was an interval of approximately 20 second during the BFM test to align the working distance and eyes.

Calculation of BFM

Data for eye positions, aberrations, and pupil sizes in both eyes were exported to an Excel file (Microsoft

Co., Ltd., Redmond, WA). Data were excluded when the pupil diameter changed by more than 2 mm/frame due to blinking,²⁸ replacing the missing value with a linearly interpolated value using Origin Pro 8.1J (OriginLab Co., Northampton, MA).

The nondominant eye position data collected during the 50-second measurement periods were averaged over the three trials before and after the visual task. The binocular fusion break time (T_B) was calculated from the nondominant eye position, as shown in Figure 2. We defined two baselines, $Base_{min}$ and $Base_{max}$, where $Base_{min}$ was the average eye position of three trials during the 2 seconds after the beginning of measurement when the transmittance of the liquid crystal shutter was equal for both eyes, and $Base_{max}$ was the average eye position of three trials during the 2-second period between 25 and 27 seconds, when the difference of transmittance between the eyes was greatest. The deviation of the nondominant eye (D_n) was calculated as $(Base_{max} - Base_{min})$, and the points at which the deviation in the nondominant eye reached 10% and 90% of the total amplitude during the fusion break phase were determined as $0.1 D_n$ and $0.9 D_n$, respectively. A linear regression line was created using the nondominant eye positions at $0.1 D_n$ and $0.9 D_n$, and T_B was determined as the point where this line intersected $Base_{min}$ (Fig. 2).

BFM was calculated using the following equation:

$$\text{Binocular fusion maintenance (BFM)} = 1 - \frac{\text{Transmittance}_{(\text{nondominant eye})} \text{ at } T_B}{\text{Transmittance}_{(\text{dominant eye})}} \quad (1)$$

Conventional Tests

Fusional Vergence Range

To measure the fusional vergence range, the subject fixated at a target placed at a distance of 5.0 m, with full-corrected spectacles. A prism bar was placed in front of the nondominant eye. The diopter (D) of the prism was increased until the subject perceived diplopia or one eye deviated from the fusional position. The dioptric value of the breakpoint was determined as the fusional vergence range.

Near Point of Convergence

To measure the NPC, the subject was instructed to fixate at an accommodative target. An examiner then moved the target from a far to a near position until the subject perceived diplopia or one eye deviated from the fusional position. The distance from the

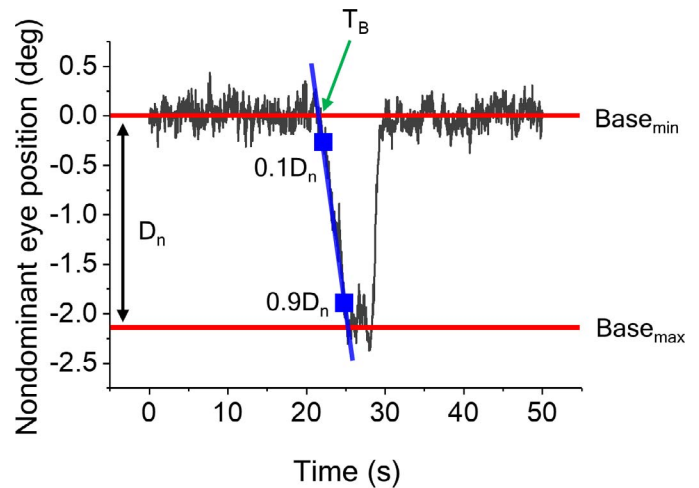


Figure 2. Calculating the binocular fusion break time. $Base_{min}$ and $Base_{max}$ are the average eye positions during the 2 seconds after the start of measurement and the 2 seconds between 25 seconds and 27 seconds, respectively. D_n is the range of the nondominant eye position, calculated as $(Base_{max} - Base_{min})$, with $0.1 D_n$ and $0.9 D_n$ indicating the points at which the amplitude of deviation in the nondominant eye reached the 10% and 90% of D_n in the binocular fusion break phase. The linear regression line (in blue) was created from $0.1 D_n$ and $0.9 D_n$. The binocular fusion break time, T_B , is the point where the linear regression line intersects with $Base_{min}$.

bridge of the nose to the breakpoint was measured with a ruler and was determined as the NPC. If the measured value was less than or equal to 1 cm, it was recorded as 1 cm.²⁹

High-Frequency Component in the Microfluctuations of Accommodation

Refractive power in the dominant eye during the onset of BFM measurement and at 34.2 seconds (i.e., at the 1024th measurement point) after onset was recorded by the BWFA with a central 4.0-mm diameter. The data were then fast Fourier transformed to determine the power spectrum components. The magnitude of power in the range between 1.3 and 2.2 Hz was integrated and defined as the HFC.^{30,31} The HFC values were averaged over three trials before and after the visual task.

The Visual Task

A three-dimensional (3D) game, Mario Cart 7 (New 3DS-LL; Nintendo Co., Ltd, Kyoto, Japan) was used as a visual task because visual fatigue is more likely to be induced by viewing 3D images compared with two-dimensional (2D) images.^{8,9,18} The new 3DS-LL is a portable game device that

Symptom questionnaire

Initials: _____ (Age: _____) Date: _____

ID: (subject / patient) # _____ Session: (before / after) _____

Q1. How tired are your eyes?

0 1 2 3 4
very fresh n.p. mildly tired moderately tired very tired

Q2. How clear is your vision?

0 1 2 3 4
very clear clear mild blur moderate blur much blur

Q3. How do your eyes feel?

0 1 2 3 4
very fresh n.p. mild strain moderate strain severe strain

Q4. How tired is your back?

0 1 2 3 4
very fresh n.p. mild tired moderate tired very tired

Q5. How tired is your neck?

0 1 2 3 4
very fresh n.p. mild tired moderate tired very tired

Q6. How severe is your headache?

0 1 2 3 4
very fresh n.p. mild ache moderate ache severe ache

Q7. How sleepy do you feel?

0 1 2 3 4
very fresh n.p. mildly sleepy moderately sleepy very sleepy

Figure 3. The subjective symptom questionnaire. Q1 through 3 were designed to assess subjective eye symptoms and Q4 through 7 to assess physical and mental discomfort. The total scores for Q1 through 3 were used to assess visual fatigue resulting from the visual task. n.p., no problem

provides 3D images viewable by the naked eye. It is equipped with a 4.88-inch 3D-display with a resolution of 800×240 pixels. Maximum stereo parallax of New 3DS-LL can change between 0° and -1° , which is controlled by a hardware. In the present study, maximum stereo parallax during visual task was set to an uncrossed disparity of 1° . Illuminance of the display was 150 cd/m^2 , measured using a luminance meter (BM-8; Topcon Corp.).

The task took place in a well-lit room at 270 lx in compliance with Japanese Industrial Standard Z 9110 in 2010. The subject was instructed to sit on a chair and to play Grand Prix mode at approximately 33 cm for 30 minutes, with full-corrected glasses at a near distance (33 cm).

1. Subjective symptom questionnaire

2. Fusional vergence range

3. NPC

4. BFM and HFC (simultaneous measurement)

5. Visual task (30 min)

6. BFM and HFC (simultaneous measurement)

7. NPC

8. Fusional vergence range

9. Subjective symptom questionnaire

Figure 4. Experimental procedure. The BFM test was performed three times before and after the visual task; subsequently, two of three BFM data in the previsual task were extracted randomly to estimate the repeatability between single measurements.

Questionnaire About Subjective Symptoms

The subjects were asked to complete a subjective symptom questionnaire at the beginning and end of the examination. The questionnaire was based upon earlier studies (Nakazawa et al.,¹ Sheedy and Bergstrom,⁷ and Hoffman et al.⁸) and presented subjects with the seven basic questions shown in Figure 3. Questions (Q) one through three were designed to assess subjective eye symptoms, and Questions four through seven assessed physical and mental discomfort. Each question was scored from zero to four, with the subject asked to choose one score for each question.

In this study, subjective visual fatigue resulting from the visual task was defined by a difference in the total of the three eye symptom scores (Q1–3) before and after the visual task of greater than or equal to 3 points.

Experimental Procedure

Each subject underwent the tests and task in the following order of Figure 4. The total examination time was 60 to 90 minutes.

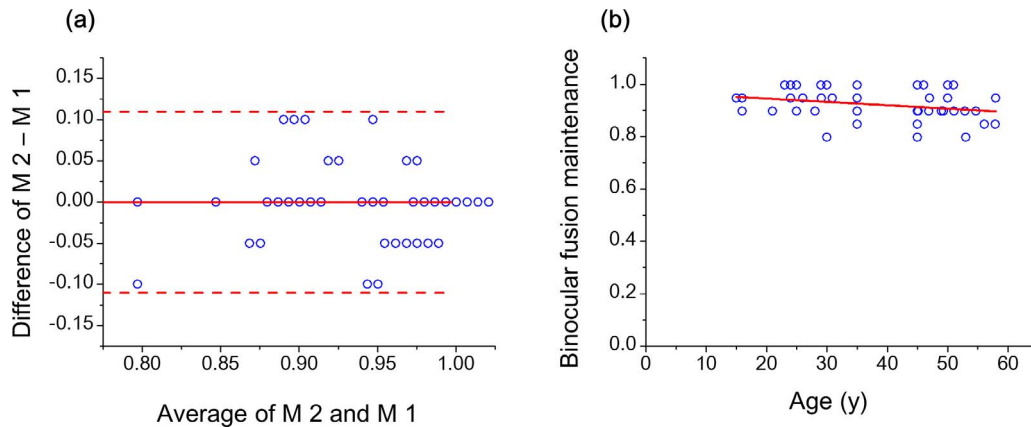


Figure 5. Reproducibility of the binocular fusion maintenance measurement (a), and changes with age (b). (a) Reproducibility of the binocular fusion maintenance test. M1 and M2 were randomly extracted as two of the three trials in BFM before the visual task. The *solid red line* shows the mean value of the difference between M1 and M2. The *red dashed lines* indicate 95% limits of agreement that is defined the mean ± 1.96 SD. (b) Relationship between binocular fusion maintenance values and the subjects' ages. The BFM value was the average of three measurements before the visual task. The *red line* is the linear regression line.

Statistical Analysis

The reproducibility of the measurements of BFM test was analyzed using a Bland–Altman plot.^{32,33} Data were extracted for two of three measurements at random during the previsual task. Fixed and proportional bias between the two measurements were analyzed with the Wilcoxon signed-rank test and single linear regression analysis. The mean value of the difference between the two measurements determined that there was a reproducibility of 0.04 or less if there was no fixed and proportional bias, because BFM changes in 0.05 steps.

To assess the effect of the visual task, the pre- and postvisual task differences in BFM, fusional vergence range, NPC, HFC, and subjective symptom scores were assessed using the Wilcoxon signed-rank test after the assessment of normality using the Shapiro–Wilk test. To evaluate the relationship between objective and subjective determinations of visual fatigue, we evaluated the correlation between the change (postvalue – prevalue) in testing values (BFM, fusional vergence range, NPC, and HFC) and the change in total subjective eye symptom score (Q1 + Q2 + Q3), using a single linear regression analysis.

To estimate the diagnostic accuracy of the tests for assessing visual fatigue, we plotted receiver operating characteristic (ROC) curves and calculated the corresponding area under each curve (AUC) that is mathematically equivalent to the Wilcoxon signed-rank test. We determined AUC for BFM and conventional tests (aggregated fusional vergence range, NPC, and HFC). We then compared the

AUCs of the BFM and conventional tests within each factor for all subjects.

IBM SPSS Statistics v23 (IBM Corp., Armonk, NY) and R version 3.2.3 (<http://www.r-project.org/>) were used to determine the significance of the differences and a *P* value less than 0.05 was considered statistically significant.

Results

In total, 40 of 44 subjects aged 38.2 ± 12.9 years (mean \pm SD; range, 15–58 years) were enrolled in this study. The mean refractive errors (spherical equivalent, SE) of the subjects' right and left eyes were -2.81 ± 3.09 D and -2.93 ± 3.05 D, respectively. The best-corrected visual acuity at distance for all subjects was equal to or better than 0.0 logMAR while the mean amplitude of accommodation was 3.40 ± 3.18 D, and all subjects had a stereo acuity equal to or better than 1.78 log arcsec (mean, 1.64 ± 0.84 log arcsec). The mean angles of deviation at near and at distance were 7.8 ± 7.5 and 1.5 ± 3.5 prism diopter base-in (PD-BI), respectively.

Repeatability of BFM Measurement and Aging Effects

The BFM between single measurements did not significantly differ (first measurement, 0.933 ± 0.059 ; second measurement, 0.933 ± 0.065 ; *P* = 0.78; Fig. 5a). The mean value of the differences between the two measurements was 0.000 ± 0.056 , and the correlation between the two measurements was not

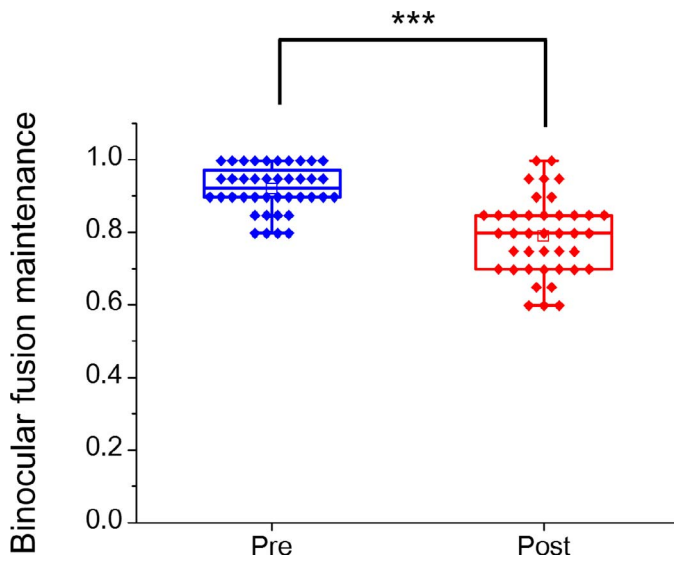


Figure 6. BFM before (blue) and after (red) the visual task. The blue and red diamonds indicate individual BFM value. BFM was determined as the mean of three trials in each subject before and after the visual task. The blue and red squares indicate the mean value of all subjects. BFM decreased significantly following the visual task. *** $P < 0.001$, Wilcoxon signed-rank test.

significant (adjusted $R^2 < 0.001$, $P = 0.49$; Fig. 5a). The 95% limits of agreement ranged from -0.111 to 0.111 .

Mean of three trials in the pre-BFM was not significantly correlated with the subject's age (adjusted $R^2 = 0.053$, $P = 0.083$; Fig. 5b). The range of BFM values across the present sample size was only approximately half of the repeatability range (Fig. 5a). Thus, age was not likely to be a factor in the range of this study.

BFM After the Visual Task

BFM decreased significantly following the visual task ($P < 0.001$; Fig. 6, Table 2). All subjects reported single vision while looking at the target before the binocular fusion break.

Conventional Tests and Subjective Questionnaire Scores After the Visual Task

The fusional vergence range, NPC, and HFC values after the visual task did not differ significantly from those before the visual task (Fig. 7, Table 2). However, the subjective symptom questionnaire scores for Q1, Q2, Q3, and Q5 were significantly greater after the visual task than before it (Q1, Q2, Q3, $P < 0.001$; Q5, $P = 0.003$; Table 2).

Table 1. Demographic Characteristics of the Subjects ($N = 40$)

Age, y	38.2 ± 12.9
Refractive error, SE	
Right eye	-2.81 ± 3.09
Left eye	-2.93 ± 3.05
Visual acuity, logMAR	
Right	-0.11 ± 0.07
Left	-0.11 ± 0.06
Accommodation, D	3.40 ± 3.18
Log stereo acuity, s	1.64 ± 0.84
Angle of deviation, PD-BI	
Near (33 cm)	7.8 ± 7.5
Distance (5.0 m)	1.5 ± 3.5

The error term is standard deviation (SD).

Relationship Between Objective Parameters and Eye Symptoms

BFM Test

The change in BFM significantly and negatively correlated with the changing total subjective eye symptom score (adjusted $R^2 = 0.752$, $P < 0.001$; Fig. 8).

Conventional Tests

The changes in fusional vergence range (adjusted $R^2 = 0.047$, $P = 0.095$), NPC ($R^2 < 0.001$, $P = 0.68$), and HFC ($R^2 < 0.001$, $P = 0.64$), were not significantly correlated with the change in total subjective eye symptom score (Fig. 9).

Diagnostic Accuracy of Visual Fatigue

The BFM test results significantly improved the diagnostic accuracy for visual fatigue compared with the conventional tests (BFM test: AUC = 0.905; 95% confidence interval [CI], 0.808–0.993; Conventional test: AUC = 0.616; 95% CI, 0.437–0.805; $P = 0.007$; Fig. 10).

Discussion

Binocular Fusion Maintenance Test

We have developed a binocular wavefront sensor equipped with liquid crystal shutters to quantitatively evaluate the ability of subjects to maintain binocular fusion (Fig. 1). BFM could not be evaluated precisely using the conventional red-filter ladder because this did not allow a linear reduction in the intensity of

Table 2. Mean Results for All the Subjects ($N = 40$)

Test	Visual Task		P Value
	Pre	Post	
Binocular fusion maintenance	0.923 ± 0.061	0.791 ± 0.106	<0.001
Fusional vergence range, PD	27.23 ± 9.13	26.23 ± 8.43	0.49
NPC, cm	4.15 ± 3.41	3.78 ± 3.19	0.166
HFC, $D^2/Hz \cdot 10^{-2}$	0.08 ± 0.14	0.07 ± 0.11	0.37
Subjective symptom questionnaire			
Q1	0.97 ± 0.79	2.12 ± 0.72	<0.001
Q2	0.57 ± 0.47	1.27 ± 0.82	<0.001
Q3	0.97 ± 0.60	2.00 ± 0.92	<0.001
Q4	1.20 ± 0.82	1.45 ± 1.07	0.069
Q5	1.20 ± 0.82	1.65 ± 1.06	0.003
Q6	0.55 ± 0.49	0.75 ± 0.89	0.154
Q7	0.77 ± 0.59	0.97 ± 0.88	0.20

The error term is SD. The pre- and postvisual task differences were analyzed with the Wilcoxon signed-rank test.

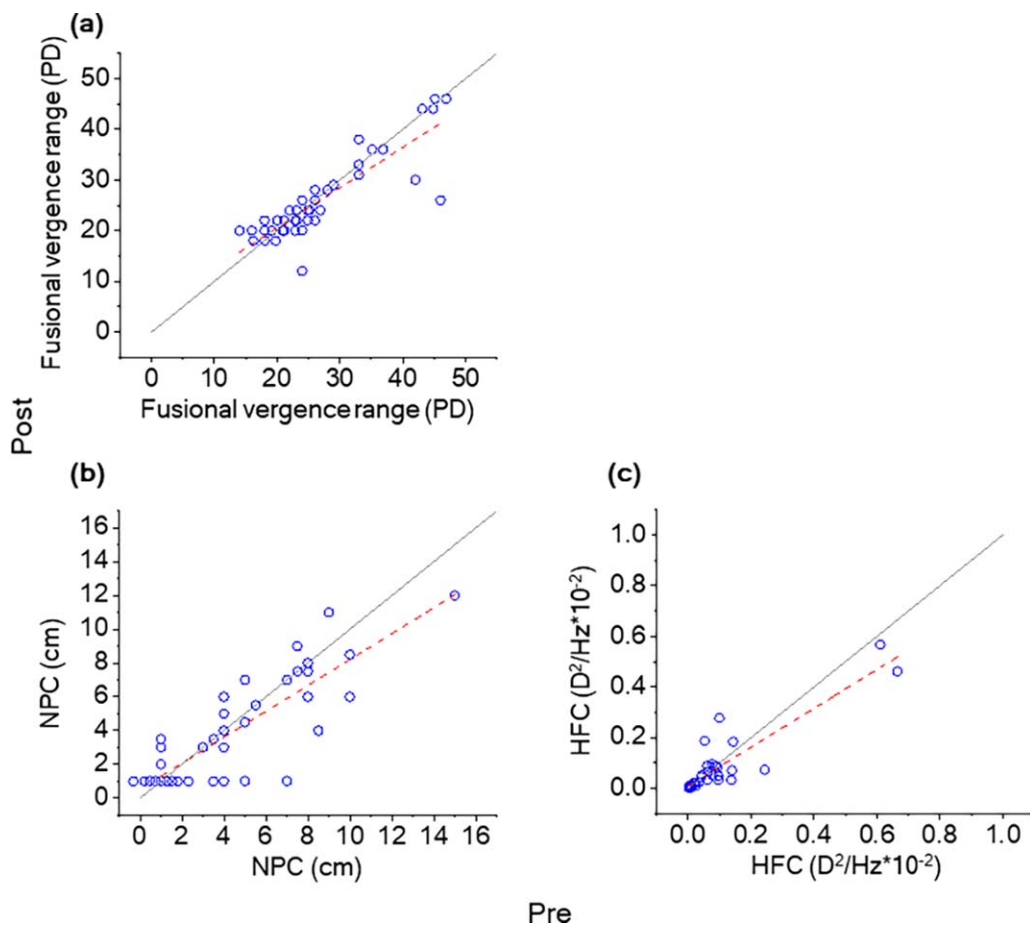


Figure 7. Conventional test results pre (x-axis) and post (y-axis) the visual task. The red-dashed and gray lines indicate regression and equation lines. The fusional vergence range, NPC, and HFC values after the visual task did not differ significantly from those before the visual task. (a) Fusional vergence range. (b) NPC. (c) HFC in microfluctuations of accommodation.

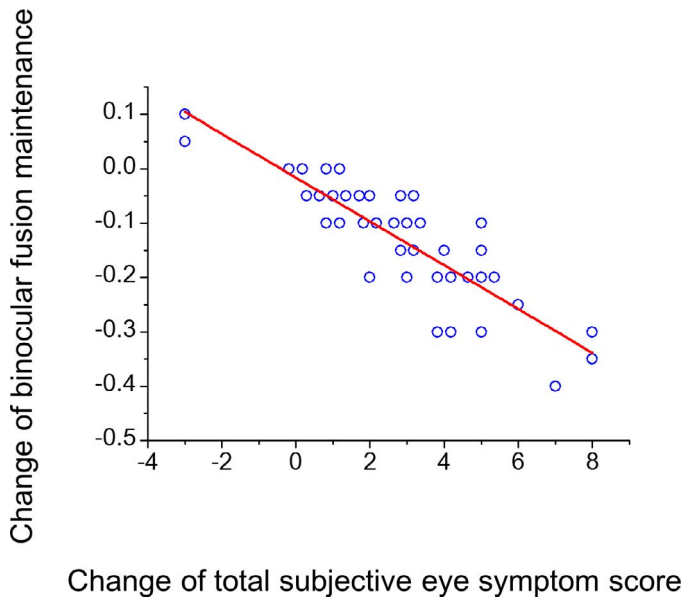


Figure 8. Relationship between the changes after the visual task in binocular fusion maintenance values and in total subjective eye symptom scores. The regression line is indicated in red.

incoming light.²⁵ In contrast, our instrument was able to change the transmittance of the liquid crystal shutter linearly and sequentially. The BFM test using this equipment produced reproducible results (Fig. 5a), which suggests that the test is suitable for the quantitative evaluation of binocular fusion. Furthermore, the BFM values did not depend on the subjects' ages (Fig. 5b); therefore, BFM may have an advantage over other methods that use accommodation to evaluate asthenopia because presbyopic people show prolonged NPC and reduced accommodation.^{31,34-36} It has been reported that binocular fusion is preserved even in the elderly population; 71% of subjects over 65 years of age showed stereopsis, although stereopsis gradually decreases after 40 years of age.^{37,38}

BFM significantly decreased following the visual task (Fig. 6). This finding suggests that many individuals perceive diplopia and blurred vision following computer use.^{2,19,39} Earlier studies have shown that stereoacuity is best under photopic and is

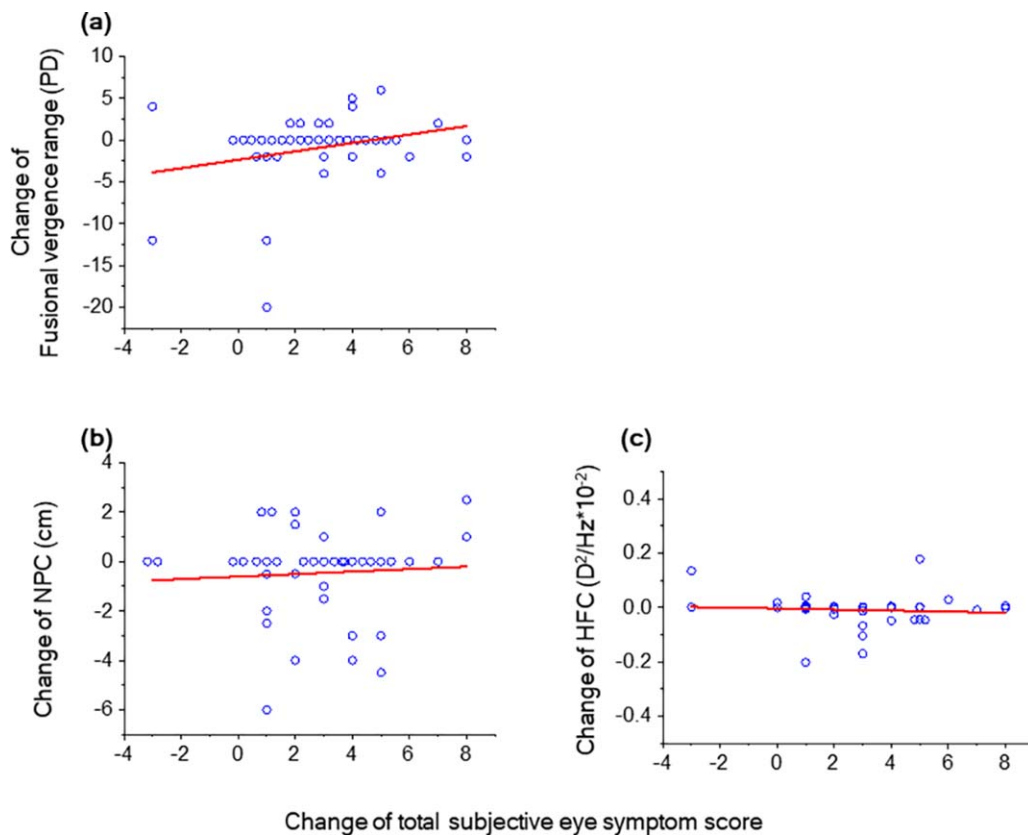


Figure 9. Relationship between the changes after the visual task in the conventional test scores and in the total subjective eye symptom score. The red lines indicate the regression lines. (a) Fusional vergence range. (b) NPC. (c) HFC in microfluctuations of accommodation.

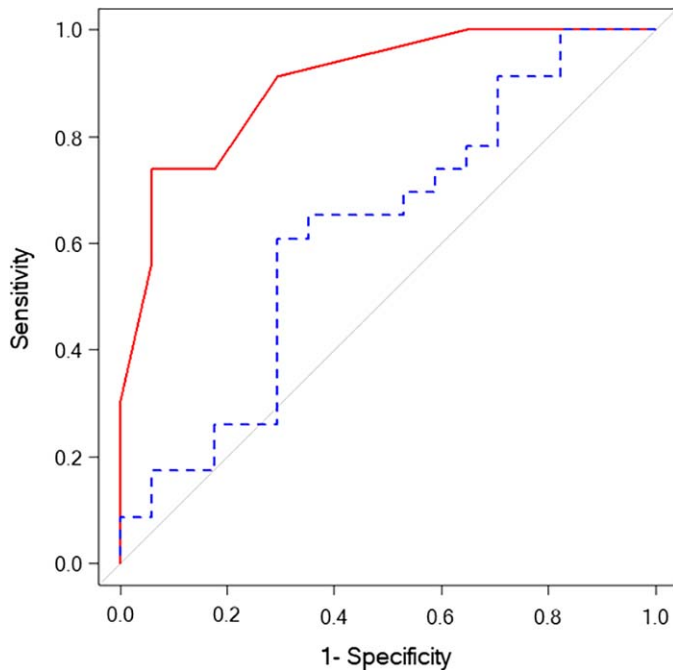


Figure 10. Diagnostic accuracy for visual fatigue of the binocular fusion maintenance test (*red*) and conventional tests (*blue*). The plots are receiver operating characteristic curves. The *red* and *blue* curve is for the BFM test and conventional tests (aggregated fusional vergence range, NPC, and HFC in microfluctuations of accommodation). The greater area under the *red* curve (binocular fusion maintenance test) showed the greater diagnostic accuracy for visual fatigue, as measured by the total subjective eye symptom score.

reduced under mesopic and scotopic conditions.^{40,41} We set the illumination of BFM test and visual task at 270 lx. BFM test started the transmittance of both eyes equivalent to 23.0%, and dark- and light-adapted phases of the BFM was 20 seconds. Therefore, we consider that the sensory adaptation may not have a large effect for binocular fusion in the present study.

Conventional Tests

Fusional vergence range and NPC did not differ significantly between before and after the visual task for 30 minutes (Figs. 7a, 7b). Sedaghat et al.¹⁵ compared fusional vergence between asthenopic and asymptomatic individuals and showed no significant difference between the two groups in the fusional vergence range at distance. Gunnarsson and Soderberg reported that NPC in office workers was significantly prolonged by computer use for more than 8 hours.⁴² Therefore, we consider that the visual task may have been too short in this study to determine significant differences in NPC.

HFC also did not significantly different between before and after the visual task (Fig. 7c). This finding supports the work of Maeda et al.,¹⁷ which showed in adults that HFC did not change significantly after viewing a 3D video for 90 minutes. In contrast, Jeng et al.¹⁸ reported that HFC increased in adults after viewing a 3D display for 15 minutes. As mentioned in the Methods section, BFM measured simultaneously with HFC significantly decreased following the visual task in this study. These findings suggest that there may be a problem with the reproducibility of HFC measurements.

Subjective Eye Symptoms and Binocular Fusion Maintenance

The subjects' subjective eye symptom scores increased significantly after the visual task compared with initial scores (Table 2). Our results support and reinforce previous evidence that visual fatigue and discomfort were induced by 3D visual tasks in young and presbyopic adults.^{5,7-9}

The significant correlation between symptom score and BFM (Fig. 8) strongly suggests that binocular stress may induce symptoms of eye and vision fatigue. Because none of the conventional tests showed a significant correlation with the change in total subjective eye symptom score (Fig. 9), these vergence and accommodation measures may not be useful standards for assessing visual fatigue. This conclusion is strengthened by further observations that these parameters have limitations with reproducibility^{13-15,17,18} and show aging effects.^{35,36}

Diagnostic Accuracy for Visual Fatigue

Using the BFM test results significantly improved the diagnostic accuracy for visual fatigue compared with using the conventional tests (Fig. 10). The present finding suggests that BFM might be affected sooner than conventional measures, and thus could serve as a better tool for diagnosis.

Conclusions

The ability to maintain fusion diminishes after binocular stress. BFM shows a good correlation with subjective eye symptoms. This correlation is stronger than that shown by conventional measures, suggesting that BFM may be used for either detecting or predicting eye and vision problems due to binocular stress.

Acknowledgments

Supported by grants from an Asian CORE Program, Japan Society for the Promotion of Science (JSPS), Advanced Nano Photonics Research and Education Center in Asia (TF); the JSPS Core-to-Core Program, A, Advanced Research Networks (TF); The Ministry of Education, Culture, Sports, Science and Technology Japan, Grant-in-Aid for Scientific Research B, J16H05487 (TF); and the Research Fellowship for Young Scientists, JSPS, 17J01295 (MH).

Disclosure: **M. Hirota**, WO2017159225 (P); **T. Morimoto**, None; **H. Kanda**, None; **T. Endo**, None; **T. Miyoshi**, None; **S. Miyagawa**, Topcon Corp. (E), WO2017159225 (P); **Y. Hirohara**, Topcon Corp. (E); **T. Yamaguchi**, Topcon Corp. (E), WO2017159225 (P); **M. Saika**, Topcon Corp. (E), WO2017159225 (P); **T. Fujikado**, Topcon Corp. (F), WO2017159225 (P)

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