Research Article

Visual Fatigue Estimation by Eye Tracker with Regression Analysis

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The traditional way to detect visual fatigue is to use the questionnaire or to use critical fusion frequency of high-frequency exchanges due to eye fatigue. The objective of this study was to explore whether eye movement behavior can be used as an objective tool to detect visual fatigue. Thirty-three participants were tested in this study. Their subjective visual fatigue survey, critical fusion frequency, and eye tracker of one minute gaze were measured before and after 20 minutes visual fatigue task. There were significant differences before and after visual fatigue task on survey and eye tracker-derived features. By multiple regression analysis with four eye tracker features, total fixation time duration of the inner circle, longest continuous duration of inner circle viewing time, maximum saccade distance, and focus radius, the regression R square value was greater than 0.9 for all critical fusion frequency data and when subjective visual fatigue assessment was greater than 12 points. In conclusion, eye movement behavior can be used to detect visual fatigue more sensitively even than the traditional critical flicker fusion assessment. Eye tracker can also provide well regression model to fit traditional critical fusion frequency measurement and subjective visual fatigue survey.

1. Introduction

As electronic products become more popular, people's eyes were attracted on monitors for a long time, whether for work, study, or entertainment. This long-term use of the eye has already caused a decrease in vision. Many previous studies have shown that vision loss is related to long-term visual fatigue treatment, and visual fatigue also hinders students' learning, as well as the health of workplace workers, and even increase the frequency of road drivers' car accidents. Therefore, the visual fatigue study attracts great atten-

tion from academics and industry. Studies on visual fatigue have focused on exploring how work-related tasks affect visual fatigue and on detecting visual fatigue to improve traffic safety; some studies have focused on exploring the relationship between visual fatigue and attention. Methods for estimating visual fatigue can be divided into two types: subjective and objective. Subjective visual fatigue assessment is usually performed through questionnaires based on self-report information [1, 2], while objective visual fatigue assessment involves critical fusion frequency [3], and also tools based on physiological signals, such as an EOG, are
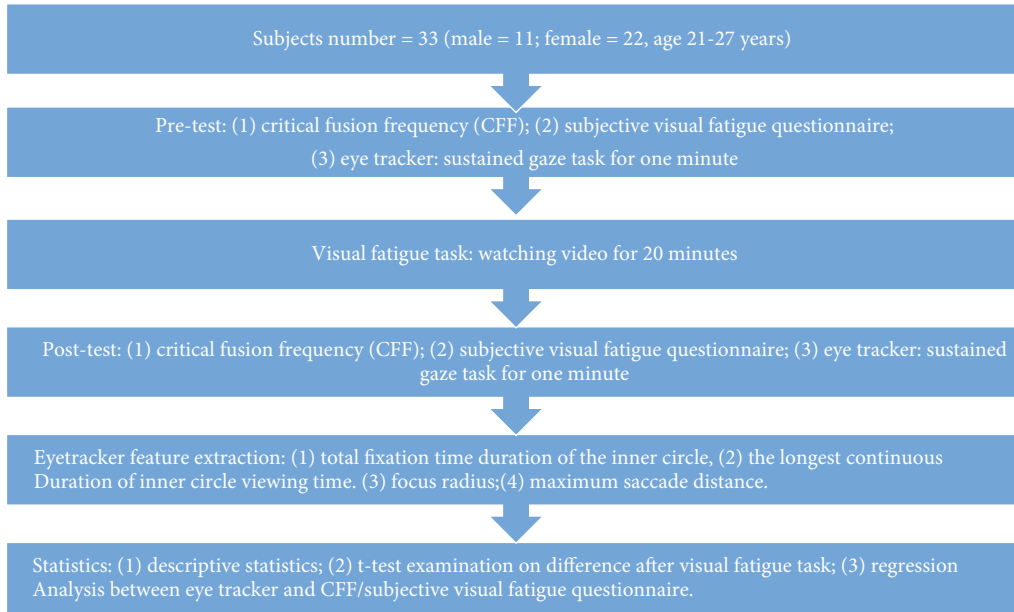
Figure 1: Experimental flow chart.

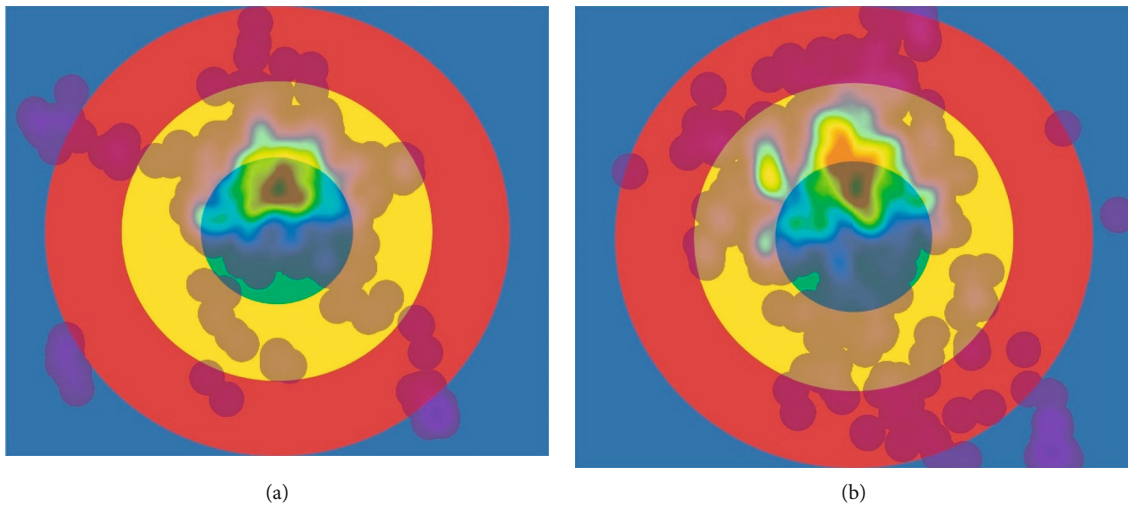(a)   (b)

Figure 2: Concentric circles used in the sustained gazing task and their target areas (also called areas of interest (AOIs)). The AOI in the picture is the area inside the green circle. Heat map picture of a subject before and after visual fatigue task is shown in (a, b), respectively.

Table 1: Questionnaires and CFF results before and after fatigue task. $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Item		Content	Pretest Mean (SD)	Posttest Mean (SD)	p value
Subjective visual fatigue assessment	Q1	I have difficulties in seeing	2.64 (2.15)	2.85 (2.14)	0.466
	Q2	I have a strange feeling around the eyes	1.82 (1.65)	3.33 (2.56)	≤0.001***
	Q3	My eyes feel tired	3.61 (2.26)	5.85 (2.86)	≤0.001***
	Q4	I feel numb	2.06 (1.71)	4.12 (2.99)	≤0.001***
	Q5	I have a headache	1.73 (1.31)	3.24 (2.32)	0.002**
	Q6	I feel dizzy looking at the screen	2.85 (2.21)	4.03 (2.49)	0.002**
		Total	14.7 (9.27)	23.42 (12.24)	≤0.001***
Objective visual fatigue assessment		Critical fusion frequency (CFF)	37.77 (12.92)	39.5 (11.84)	0.195

TABLE 2: Eye tracker results before and after fatigue task. $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Parameters	Pretest		Posttest		p value
	Mean	SD	Mean	SD	
Total fixation time duration of the inner circle (sec)	41.6	17.3	35.3	10.5	0.013*
Longest continuous duration of inner circle viewing time (sec)	5.3	7.6	2.5	2.7	0.009**
Maximum saccade distance (a.u.)	675.8	222.5	849.0	249.0	≤0.001***
Focus radius (a.u.)	74.5	43.5	112.1	78.1	≤0.001***
Accuracy score	67.9	21.6	59.5	19.7	0.009**
Precision score	54.8	22.4	35.6	23.9	≤0.001***

TABLE 3: Eye tracker results before and after fatigue task of a subject derived in Figure 2.

Eye tracker parameters	Before	After
Total fixation time duration of the inner circle (sec)	43.1	33.6
Longest continuous duration of inner circle viewing time (sec)	3.6	2.2
Maximum saccade distance (a.u.)	745.2	939.0
Focus radius (a.u.)	96.2	126.0
Accuracy score	70.5	60.5
Precision score	40	18

used to investigate visual fatigue by detecting the blinking rate of the eye [4, 5]. Binocular vision [6], EEG and pupil constriction rate [7], and eye tracking [8, 9] are also popular tools for studying visual fatigue. Among these measurement methods, eye tracking is a rapid and noninvasive method for objectively collecting data. Researchers use this method to investigate human attention, reading, and cognitive processes. Eye tracking results are considered to reflect the process of shifting one's internal visual attention [10–13].

The main question that the present study sought to answer is whether eye movement behavior be more sensitive than traditional method to detect visual fatigue and visual fatigue index correlation between eye tracker and other traditional methods. We designed a "fatigue-related task" to generate visual fatigue and a "sustained gaze task" to investigate the behavior of the eye movement of participants by using an eye tracker. Additionally, we adopted the subjective visual fatigue assessment that was developed by Heuer et al. [1] and critical fusion frequency [14] to estimate visual fatigue. The differences between these three approaches are compared. Multiregression is also used to investigate the multifactors as a visual fatigue index [15].

The rest of the paper is organized as follows. Section 2 contains the literature review. Section 3 contains the methodology. Section 4 contains the results. Section 5 and Section 6 contains the discussion and conclusions.

2. Literature Review

In recent years, the research on visual fatigue has received much attention. Kang et al. studied watching APP for 20 minutes with VR device, and their results showed that there was a significant difference in visual fatigue index using subjective fatigue questionnaire [16]. Hirota et al. compared the

visual fatigue difference between head-mounted display for virtual reality and two-dimensional display. The visual fatigue measured by subjective fatigue questionnaire and Binocular fusion maintenance both showed that there was no difference between the degree of visual fatigue caused by these two display devices [17]. Yu and Akita used CFF to measure the difference in visual fatigue under various luminance ratios of tablet computers [18]. Critical flicker-fusion frequency (CFF) test is to measure retinal response. When visual fatigue, the visual response is no longer modulated with a normal critical value of 25 Hz-55 Hz [19]. It takes several minutes to measure the response frequency with CFF. Survey is another useful way to measure visual fatigue. Subjective visual fatigue questionnaire was mainly developed by Heuer et al. in 1989 [1]. The questionnaire included six items. Subjects used a 10-point scale to evaluate each item. 1 means "not at all," and 10 stands for "very much." The six questions are as follows: (1) I have difficulties in seeing. (2) I have a strange feeling around the eyes. (3) My eyes feel tired. (4) I feel numb. (5) I have a headache. (6) I feel dizzy looking at the screen. There are many questionnaires developed to measure visual fatigue. The most commonly used in recent years is the simulator sickness questionnaire (SSQ) [20], which contains 16 items and has been used in more than 300 papers. Nevertheless, Heuer's questionnaire is still widely used due to its simplicity and ease of measurement.

Eye tracker is a measuring tool for detecting pupil movement of vision in recent years. The human eyes track certain subjects, and eye tracking modes include two states: the stop state (or "fixation") and jump state (or "saccade"). When the eye tracking mode is in the "stop" state, the visual system is in the process of encoding and handling imaging information; by contrast, when the eye tracking mode is in the

<div style="text-align:center">Table 4</div>

(a) Multiregression result of pretest subject visual fatigue score

Score (≥)	Subject no.	R^2	p value	RMSE
6	32	0.761316	≤0.001	8.57
7	26	0.812599	≤0.001	9.88
8	25	0.82065	≤0.001	8.29
9	21	0.867076	≤0.001	7.68
10	18	0.879979	≤0.001	7.78
13	16	0.884762	≤0.001	8.00
14	15	0.8949	≤0.001	7.81
15	13	0.919797	≤0.001	7.16
17	12	0.928782	≤0.001	6.93
18	11	0.938531	≤0.001	6.60
19	10	0.942586	0.0017	6.55
20	9	0.966895	0.0020	5.12
22	8	0.97889	0.0049	4.21
23	7	0.977748	0.0296	4.45
25	5	0.999106	N.A.	

(b) Multiregression result of pretest CFF data

CFF (≤)	Subject no.	R^2	p value	RMSE
76	32	0.86	≤0.001	14.59
70	31	0.89	≤0.001	12.19
69	30	0.90	≤0.001	11.43
68	29	0.94	≤0.001	8.62
47	28	0.96	≤0.001	6.67
46	27	0.95	≤0.001	6.65
38	26	0.96	≤0.001	6.10
36	25	0.96	≤0.001	5.99
35	22	0.96	≤0.001	5.90
34	16	0.96	≤0.001	5.55
33	11	0.98	≤0.001	3.79
32	10	0.98	≤0.001	3.80
31	7	0.98	≤0.001	2.96
30	6	0.98	0.112705	2.86

<div style="text-align:center">Table 5</div>

(a) Multiregression result of posttest subject visual fatigue score

Score (≥)	Subject no.	R^2	p value	RMSE
8	31	0.80	≤0.001	11.81
9	29	0.82	≤0.001	11.51
10	28	0.83	≤0.001	11.28
11	26	0.87	≤0.001	10.39
12	24	0.90	≤0.001	11.36
13	23	0.91	≤0.001	8.90
14	22	0.91	≤0.001	8.81
15	21	0.92	≤0.001	8.81
16	20	0.93	≤0.001	8.21
17	19	0.95	≤0.001	7.29
18	18	0.96	≤0.001	6.23
25	17	0.97	≤0.001	5.76
26	14	0.97	≤0.001	5.36
27	13	0.97	≤0.001	5.45
29	12	0.98	≤0.001	5.01
30	10	0.98	≤0.001	4.47
31	9	0.98	≤0.001	4.62
32	8	0.98	0.0017	4.14
34	7	0.99	0.0106	3.71
37	6	0.99	0.1000	4.00

(b) Multiregression result of posttest CFF data

CFF (≤)	Subject no.	R^2	p value	RMSE
73	31	0.91	≤0.001	12.27
68	30	0.93	≤0.001	10.52
67	29	0.93	≤0.001	9.99
57	28	0.94	≤0.001	8.41
55	27	0.95	≤0.001	7.46
52	26	0.95	≤0.001	7.29
48	25	0.96	≤0.001	6.28
41	23	0.98	≤0.001	4.18
39	22	0.99	≤0.001	3.22
38	21	0.99	≤0.001	2.88
37	20	0.99	≤0.001	2.60
36	18	0.99	≤0.001	2.60
35	17	0.99	≤0.001	2.68
34	14	0.99	≤0.001	2.60
33	11	0.99	≤0.001	2.36
32	9	0.99	≤0.001	2.38

"jump" state, the visual system is resting [21–24]. Therefore, in time-domain analysis, fixation time and fixation count are used to investigate the depth of visual information processing [25] and have been reported to reflect the complexity of environmental information and the degree of involvement of cognitive processing [26–30]. In space-domain analysis, fixation position and saccade length are considered key indexes for understanding the depth of visual information processing [5]. Our previous research established gaze parameters on eye tracker. Gaze accuracy and gaze precision were used to model the subject's gaze attention score [31]. A previous study showed that eye tracking data were used for metal fatigue detection [32, 33]. Marandi et al. investigated visual fatigue with a 40-minute task. Their results showed that eye blink duration, eye blink frequency, pupil dilation range, and fixation duration increased whereas saccade peak velocity and saccade duration decreased [34]. Eye fatigue is increasing in various display systems, whether on head-mounted displays [9] or on LED TVs [35]. According to Koo et al. study [28], the pupil diameter change accompanied with subjective fatigue during watching video on LED, and the pupil diameter is also one visual parameter derived

from eye tracker. Therefore, the other eye tracker-derived parameters have potential to be highly related with visual eye fatigue. The goal of this study is to investigate the relation among eye tracker-derived parameters and the other two visual fatigue measurements.

3. Materials and Methods

3.1. Subject Information. Thirty-three young adults were included in this study: 11 men (33.3%) and 22 women (66.7%), ranging from 21 to 27 years (mean = 22.06; SD = 1.41). Participants were recruited from students in the Taiwan area. Each subject will know the description of the experimental procedure before signing the experiment and signing the experimental consent form.

3.2. Experiment Procedure. All participants underwent the visual fatigue and sustained gazing tasks. First, during the pretest stage, visual fatigue was assessed by subjective visual fatigue questionary and CFF; eye movement was subsequently assessed (sustained gaze task) using the eye tracker. Second, in the fatigue stage, participants were asked to perform the fatigue-related task for 20 minutes. Finally, in the posttest stage, visual fatigue and eye movement were retested after participants had finished the fatigue-related task. In the fatigue-related task, participants looked at landscape pictures and dynamic pictures, such as a white-and-black checkerboard and landscape pictures (each picture appeared on screen for 0.5 seconds) for 20 minutes. The sustained gazing task included two sessions. Participants sat at a distance of 65 cm in front of an eye tracker and were asked to look at the target area of each picture for 60 seconds. In Section 1 (the picture of concentric circles), the participants received the following instructions: "Please look at the green circle area and try not to blink while keeping your head and body still." The experiment procedure is demonstrated in Figure 1.

3.3. Stimuli and Apparatus. In the fatigue-related task, we used STIM2 (Compumedic Neuroscan, Charlotte, NC, USA) to edit the test materials (that is, the pictures); materials were displayed on a computer monitor. In the sustained gaze task, we used a picture of concentric circles (Figure 2) to track the eye movements of the participants. These pictures were taken by the author. We used the Mangold Vision software (Mangold, Arnstorf, Germany) to edit the materials; the materials were displayed on the computer monitor. The eye tracker was an Eyetech VT2 mini (Mangold). Gaze data were sampled at 80 Hz. Data coding and analysis was performed using the aforementioned Mangold Vision software.

3.4. Eye Tracker Features. The features of the eye tracker are defined as shown in previous studies [20]; two are accuracy-related parameters and two are precision-related parameters. Accuracy-related parameters are (1) total fixation time duration of the inner circle and (2) the longest continuous duration of inner circle viewing time. Precision-related parameters are (3) focus radius and (4) maximum saccade distance.

3.5. Statistics. All data are represented as mean and standard derivation (std), including six subjective visual fatigue assessment questionnaires, total subjective visual fatigue assessment, critical flicker fusion data, and six parameters derived from the eye tracker. Data difference between pretest and posttest is examined by paired t-test. The significance value was set at 0.05.

Multiregression is also applied. The regression formula is $y = f(x)$. There are two y variables and two combinations of x variables. Y1 is the the CFF, and y2 is subjective visual fatigue score. Input variables are combination of four eye tracker features:

(1) Total fixation time duration of the inner circle (sec)

(2) Longest continuous duration of inner circle viewing time (sec)

(3) Maximum saccade distance (a.u.)

(4) Focus radius (a.u.)

R square value and p value of ANOVA examining among the parameters were also evaluated as multiregression performance evaluation. The root mean square error (RMSE) of estimated fatigue and real fatigue (inclusive of CFF and subjective visual fatigue score). The definition of RMSE is as follows:

RMSE = $\sqrt{\sum_{i=1}^{n}((\hat{y}_i - y_i)^2/n)}$, where $\hat{y}$ is the estimated fatigue and y is the original fatigue.

All statistics are operated by Excel.

4. Results

The results of visual fatigue were obtained through questionnaires and CFF. Subjective fatigue as measured using the questionnaire underwent a significant increase from 14.7 to 23.42 (standard deviation (SD) = 9.27, 12.24, $p < 0.001$) before and after the fatigue-related task, as shown in Table 1, respectively. These results indicated that the participants exhibited sufficient visual fatigue following the fatigue task. The CFF results did not indicate a significant main effect of fatigue condition (pretest mean = 37.77, SD = 12.92; posttest mean = 39.50, SD = 11.84; $p = 0.195$). Average eye tracking result before and after fatigue task is represented in Table 2. As shown in Table 2, the accuracy parameters and precision parameters would decrease after visual fatigue task. The accuracy score decreased by an average of 8 scores, while the precision score decreased by nearly 19 scores. A typical eye tracking heat map is demonstrated in Figure 2, and the subject's eye tracking data is illustrated in Table 3.

Multiregression results of subjective visual fatigue score and CFF are listed in Tables 4 and 5. Regardless of whether it is pretest or posttest, the regression of the two methods can have the effect of $R^2 > 0.9$ for the part with high fatigue scores.

5. Discussion

This study reveals an interesting result that, CFF as standard way to measure visual fatigue, the sensitivity is neither as

high as the subjective questionnaire, nor eye tracker. The fatigue task in this study is to look at dynamic pictures, such as the black-and-white checkerboard and landscape (each was displayed for 0.5 seconds) in the fatigue-related task, perhaps these dynamic pictures that quickly flashed on screen caused participants to feel subjective visual fatigue. The fatigue-related task may be an excellent experimental tool because it can quickly elicit a feeling of visual fatigue in humans—the task lasted only 20 minutes. In addition, although CFF is an objective measurement method, CFF results are also related to the operation of the subject. If the subject is accustomed to the feeling of fusion image of CFF, there will be a bias of the CFF result between two repeated measurements. The measurement bias is also possible for subjective visual fatigue questionnaire scales. Subjects will over emphasize their feelings, and the bias will be shown in their self-report. Other physiological measurement methods are used by visual fatigue detection, including eye tracker and eye blinking.

This article used a gaze-focused approach for eye trackers. This method has a norm distribution for accuracy and precision. Each subject has a pair gaze scores with accuracy and precision. For example, accuracy score = 90, which means that subject have won 89 people among 100 people. The most sensitive parameter for visual fatigue within the accuracy score is the total fixation time duration. In Table 2, the average longest continuous duration of inner circle viewing time before and after fatigue task only drops from 5.3 sec to 2.5 sec, corresponding to 89% to 85%. The average precision score decreased from 54.8 scores to 35.6 scores, due to both the focus radius and the maximum saccade distance increasing after the fatigue task. In other words, visual fatigue has a greater influence on precision than accuracy base on gaze score. Due to visual fatigue, the focus point is easy to diverge, and the max saccade is also increased. Therefore, under visual fatigue, it affects work efficiency and learning efficiency and even increases the possibility of road accidents for road drivers. This study is only for visual fatigue and is not comparable with other attention indicators. Therefore, this result only demonstrated that gaze parameters derived by eye tracker, especially precision, can be used as a novel measurement method for visual fatigue. In this experiment, the CFF did not measure the difference between fatigue tasks, but the subjective questionnaire revealed fatigue status. At the same time, the eye tracker effectively reflected the influence of fatigue.

Using multiple regression results is able to examine the possibility whether the eye tracker parameters can be used to predict the visual fatigue index. The lower the frequency of CFF and the higher the subjective questionnaire score, the higher visual fatigue. Compared to the same visual fatigue score, the R square performance of multiregression for posttest data is better than the pretest situation. Both the CFF and the subjective visual fatigue score showed the same phenomenon. The multiregression result based on four eye tracker-derived features is effective, especially for a period of visual use. Since the experiment in this article only uses 20 min video watching task, whether the eye tracker still

has a good regression performance for longer video, watching duration still further carefully examined.

The topic of visual fatigue has extended from the traditional 2D/3D monitor to VR/AR. The subjective visual fatigue questionnaire used in this research is applicable to the visual fatigue of the traditional 2D/3D monitor environment. For VR environment, SSQ is developed to investigate visual fatigue with 16 items [36]. This study uses the eye tracker index, whether it is also suitable for visual fatigue detection in the VR environment, and whether it is related to the SSQ questionnaire, which is also an interesting research topic in the near future study.

6. Conclusions

This study indicated that eye movement behavior can be used to detect visual fatigue and may therefore be a physiological indicator for assessing visual fatigue, especially on precision gaze. Second, dynamic pictures can quickly elicit a feeling of visual fatigue after a short time (20 minutes). However, self-reported visual fatigue was observed in this study but not measured in the physiological responses—whether this was because of visual fatigue or mental fatigue would be a valuable research direction for future studies. Four eye tracker-derived features are useful to predict both visual fatigue indexes with multiregression analysis.

Data Availability

Data is not suitable to be publicly achieved.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Li-Wei Chou has equal contribution with the first author.

Acknowledgments

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