# User Eye Fatigue Detection via Eye Movement Behavior

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## Abstract:
In this study we propose and evaluate a novel approach that allows detection of physical eye fatigue. The proposed approach is based on the analysis of the recorded eye movements via what is called behavioral scores. These easy-to-compute scores can be obtained immediately after a calibration procedure, via processing of such basic eye movements as fixations and saccades extracted from the raw eye positional data recorded by an eye tracker. The results, based on the data from 36 volunteers indicate that one of the behavioral scores, Fixational Qualitative Score, is more sensitive to the onset of eye fatigue than already established methods based on saccadic characteristics only.



## Author Keywords
Eye tracking; eye movements; behavioral scores; eye fatigue; human factors.

## ACM Classification Keywords
H.1.2 [Information Systems]: User/Machine Systems - Human information processing

## Introduction
People who use electronic devices, spent more and more time looking at displays [5]. Our eyes struggle to cope with such high workload that is causing eye fatigue and Computer Vision Syndrome [4]. While it is impossible to completely avoid eye fatigue, we can aim at reducing the fatigue and thus potentially reducing the consequences it causes. Several factors influence the onset of the eye fatigue. A poor-designed GUI can make physical eye workload higher due to using wrong color scheme and the structure that makes a user

conduct an excessive visual search, when another, a better-designed GUI requires less eye movements to complete a task [13]. Therefore the ability to have real-time computable assessment metrics for fatigue detection is very important because they will help develop better GUI that would reduce levels of physical eye fatigue.

Eye movement driven metrics have the potential to aid eye fatigue assessment because of their high sensitivity and real-time computation capability. Contemporary eye trackers are user friendly and non-invasive [2]. In general, the cost and usability of eye trackers were recently considerably improved, with contemporary units available for just around $100, e.g., [1].

The majority of human eye movements in HCI-related tasks are presented by fixations and saccades [6]. Fixations are executed when a user is looking at a stationary target. Rapid, ballistic eye movements that move the eye from one fixation to another are called saccades. Our work employs scores that are based on fixations and saccades for the detection of physical eye fatigue.

## Previous Fatigue-related Work

There is a substantial amount of work in detecting user's eye fatigue, but the majority of this work is saccade-based, employs considered characteristics such as: amplitude, duration, peak and mean velocity [3, 11, 12]. Only top-rated, the most expensive eye trackers with high sampling rate of 250Hz and more can provide enough accurate information for analyzing saccadic behavior, because saccades are very quick and short in duration. Fixations are frequently longer than 200ms, while the majority of saccades last less than 80ms.

Therefore, in addition to saccade-based approach we propose fixation-based approach that can be potentially be employed on a low cost eye trackers with low sampling frequency, potentially working on the mobile and wearable devices [7] and provide enough sensitivity to user's eye fatigue to be used in real-time. Ideally, fatigue-related statistical sensitivity provided by such metrics would be higher than of existing ones and they would be simple to compute. Eye Movements Behavioral Scores described next target to satisfy those requirements.

## Eye Movements Behavioral scores

Behavioral scores represent quantitative and qualitative characteristics of the eye movement behavior [9] recorded in response to a step-stimulus such as jumping dot of light presented for example during eye tracker's calibration. In general, the values of the behavior scores can signal a) meaningfulness of eye movement classification, b) eye tracking quality, c) "normality" of the captured eye movement signal. In this study by controlling for a) and b) we investigate the ability to detect "abnormality" of the captured eye movement signal which specifically translates to eye fatigue detection for the purposes of this study.

*Fixation Quantitative Score (FQnS)* represents how many fixational samples were recorded nearby current stimulus location. The FQnS, calculated by the equation (1), also takes into the account the latency associated with user reaction in response to the stimulus and considers fixations only in the meaningful proximity to the presented stimulus. The FQnS is representative of both number of exhibited fixations and their durations and has less variability that either of those metrics.

$$FQnS = 100 \cdot \frac{fixation\_detection\_counter}{stimuli\_fixation\_points} \quad (1)$$

*Fixation Qualitative Score (FQlS)* indicates the spatial accuracy of the exhibited fixations in response to the presented stimulus, calculated by the equation (2). Intuitive considerations suggest that eye fatigue would cause a user to frequently miss a target on the initial fixation and therefore some of the fixations would be located further away from the target than during normal "fresh" baseline. Part of our hypothesis is that FQlS will increase when a user becomes fatigued.

$$FQlS = \frac{1}{N} \cdot \sum_{i=1}^{N} fixation\_distance_i \quad (2)$$

*Saccade Quantitative Score (SQnS)* represents the amount of saccadic behavior captured in response to the presented stimuli calculated by the equation (3). Our intuitive considerations regarding the SQnS change during eye fatigue are similar to the ones provided for the FQlS. When a user misses the target on the initial saccadic movement, the miss is subsequently corrected with an additional saccade. These additional corrective saccades in cases when the eye overshoots or undershoots a target lead to the larger amount of saccadic behavior when compared to a baseline. Therefore, our hypothesis is the SQnS will increase when a user becomes fatigued.

$$SQnS = 100 \cdot \frac{total\_detected\_saccade\_amplitude}{total\_stimuli\_saccade\_amplitude} \quad (3)$$

In addition to the behavioral scores we consider metrics that are close to those investigated in previous research [3, 11, 12]: Average Number of Saccades (ANS), Average Saccade Duration (ASD), Average Saccade Peak Velocity (ASPV).

## Experimental Methodology

*Recording Equipment*

The data was recorded using the EyeLink 1000 eye tracker with a sampling frequency of 1000Hz. The recording was conducted on a tower mount with chin and forehead rest to improve the accuracy and reduce the noise in the recorded data. The stimulus was presented on 22 inch flat panel wide-screen LCD display with refresh rate of 60Hz. The display measured 474 x 297 millimeters and resolution was 1680 x 1050 pixels. The chinrest was located 550mm from the display. For each subject the chinrest was adjusted to ensure that primary eye position (eye is staring straight ahead) would be equal for all participants.

*Recording Procedure & Stimulus*

The horizontal step stimulus was selected for the experiment because "the effects of fatigue upon saccadic eye movements, for example in myasthenia gravis, may be tested by asking the patient to repetitively refixate between two targets" [10]. The stimulus was displayed on a black screen as a dot, consisting of a white disc sized approximately 1º with a small black point in the center. The dot performed 100 jumps horizontally with amplitude of 30º, which corresponded to the dot location +15º and -15º from the center of the display, each time the dot was stationary for 1 s. before the next jump because "after making only 30 50-deg or 80 30-deg saccades, the subject could not produce normally-shaped saccades. All further saccades would have symptoms of fatigue" [3]. Initial dot location was display's center. Each participant was instructed to follow the dot movements.

| *Task* | *S1, M(SD)* | *S2, M(SD)* |
|---|---|---|
| **Horizontal** | **2.61 (1.40)** | **2.50 (1.38)** |
| Movie clip1 | 1.25 (0.69) | 1.22 (0.42) |
| Fixational | 1.58 (0.69) | 1.63 (0.79) |
| Random | 2.56 (1.23) | 2.83 (1.38) |
| Reading | 1.85 (0.87) | 1.97 (1.03) |
| Game | 2.03 (1.08) | 2.16 (1.30) |
| Movie clip 2 | 1.13 (0.42) | 1.31 (0.67) |

**Table 1.** Task-oriented questionnaire results, on 7-pt. Likert scale

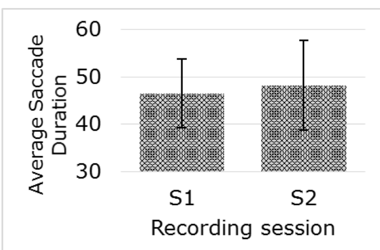


**Figure 1.** Average Saccade Duration

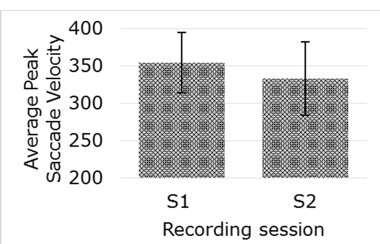


**Figure 2.** Average Peak Saccade Velocity

The presentation of this stimulus was a part of a larger ocular biometrics study that consisted of two recording sessions, S1 and S2, conducted 10 minutes apart with the total duration of the experiment not exceeding 1 hour. Each session consisted of pure fixational stimulus, horizontal stimulus (analyzed here), movie clip 1, random saccades, text reading, gaze-controlled computer game, movie clip 2.

Participants filled several questionnaires prior to recordings, between two sessions, and after all recordings. There were two 7-pt. Likert scale questionnaires related to horizontal stimulus task: a state-oriented one ("What is your eye fatigue?") before the task and task-oriented one ("How hard was the task on your eyes?") after the task.

We believe that such recording procedure allows monitoring eye fatigue onset within a single repetitive task, such as horizontal saccades stimulus and also monitor eye fatigue related changes between sessions, assuming that during S2 recordings participants' eyes became generally more fatigued than during S1.

*Participants, Eye Movement Classification & Quality of the Recorded Data*

A total of 36 participants (19 males/17 females), ages 19 – 31 years with an average age of 21.8 (SD=3.2), volunteered for the project. Verified mean positional accuracy of the recordings averaged between all screen regions was 0.88º (SD=0.27º). Average recorded data validity was 98.96% (SD = 1.02%). Collected eye movement data was classified by an I-VT algorithm [8] with the separation threshold of 70º/s [9]. Both positional accuracy and data validity numbers indicate that captured data quality was high. Eye movement classification via the I-VT algorithm based on the results of the previous study and high quality of the recorded data indicate that that the changes in behavioral scores would represent the change in the eye movement behavior, e.g., fatigue onset, rather than failures of eye movement classification or/and recording equipment.

After fixations and saccades were classified with I-VT all records were manually examined to ensure that they represent valid saccade velocity profiles. Saccades that contained blinks were removed from the final analysis. Blinks were detected by a mechanism specified by Bahill and Kallman [2]. Saccade velocity was computed by the equation (1) presented in [2] to reduce the impact of noise and variability present in the signal.

*Data Partitioning & Analysis Methods*

The recordings for each session were broken into 10 groups marked as from G1 to G10 in recording sessions S1 and S2 with 10 stimulus dot jumps per group and corresponding recorded eye movement signal. We hypothesized that such data separation would allow tracking the onset of fatigue by the metrics we have described earlier.

To research statistical differences among scores computed between groups in each session and for the averaged scores between each whole session we employed General Linear Model Repeated Measures ANOVA because each participant was recorded for all factors levels, i.e., partition groups in our case. For results that involve the comparison between all 10 groups Bonferroni correction was performed, that reduced statistically significant level to 0.005 instead of 0.05. All factors were within-subject, we did not have

| Metric name | Session 1, 10 groups, 10 saccades each | Session 2, 10 groups, 10 saccades each | Session 1 – Session 2 100 saccades each |
|---|---|---|---|
| FQnS | F(1,35)=1.378,p=0.233 | F(1,35)=2.246,p=0.047 | F(1,35)=0.412,p=0.525 |
| FQlS | **F(1,35)=7.956, p<0.0005** | **F(1,35)=8.760, p<0.0005** | F(1,35)=0.005,p=0.943 |
| SQnS | F(1,35)=1.068,p=0.376 | F(1,35)=1.2966,p=0.112 | F(1,35)=0.320,p=0.575 |
| ASD | F(1,35)=2.733,p=0.029 | **F(1,35)=3.652, p<0.005** | **F(1,35)=6.374, p<0.05** |
| ASPV | F(1,35)=0.777,p=0.579 | F(1,35)=1.596,p=0.154 | **F(1,35)=16.340, p<0.001** |
| ANS | F(1,35)=1.166,p=0.326 | F(1,35)=2.427,p=0.046 | F(1,35)=0.441,p=0.511 |

**Table 2.** Repeated-measures ANOVA results for tested scenarios

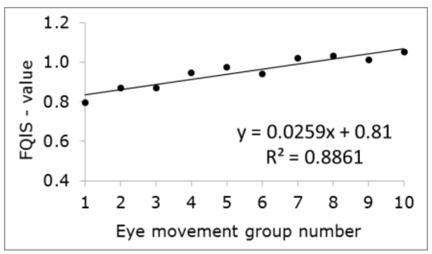


**Figure 3.** Regression for Fixation Qualitative Score. Session 1.

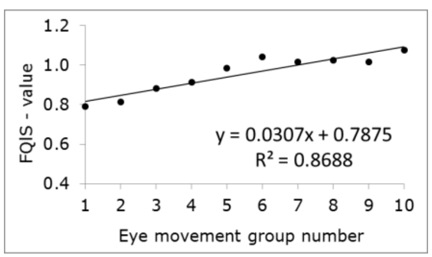


**Figure 4.** Regression for Fixation Qualitative Score. Session 2.

between-subject factors.

## Results

Results of the subjective study presented in Table 1 confirm that the horizontal stimulus induced second highest workload on users' eyes among the tasks conducted; Results of the state-oriented question "What is your eye fatigue?" are M(SD): 2.86(1.31) before S1 and 3.67(1.22) before S2. As it is shown in Table 2, significant effects were found for ASD and APSV that are used in existing methods – ASPV significantly decreases for S1-S2 (between sessions comparison) and ASD significantly increases for S1-S2 and S2 (Fig. 1, 2). Only one of the behavioral scores, FQlS, shown strong effects for S1 (within session comparison) and S2 (within session comparison) scenarios, but not S1-S2. No more effects was found, although FQnS and ANS had relatively low p-values for S2 scenario. We hypothesize if the participant's tasks lasted longer, the effect would be also found. In addition, the linear regressions for FQlS have high R-square value for S1 and S2 and approximately equal slope and shift for both sessions that makes it possibly usable as an empirical formulation for user's eye fatigue evaluation; it is shown on Fig. 3 and 4.

## Discussion

The results indicate that FQnS and the SQnS showed low sensitivity to the eye fatigue. We hypothesize that it happens due to relatively stable user reaction time and total exhibited saccade amplitude for the duration of each task that was recorded. Our results support the sensitivity to fatigue of the saccade related metrics that we adopted from the previous research.

The main contribution of our work is the finding that FQlS, which is very simple and fast to compute, is able to indicate the progression of fatigue following the progression of a fatigue inducing task. For example it is possible to see from the Fig. 3 and 4 how the FQlS increases over time and also gets refreshed between the sessions when the subjects gets some rest. None other metric has shown similar dynamics in fatigue progression as the FQlS. It should be noted that metrics from previous research can detect change in fatigue over large amount of eye movements (i.e., difference between whole recording sessions), but proposed fixation behavior metric can detect the increase in fatigue for smaller eye movement groups, thus potentially making this metric more usable for user eye fatigue detection over short periods of time and also monitoring the fatigue progression over time.

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## Conclusion and Future Work

We conducted a study to investigate eye fatigue detection capabilities of the eye movement based metrics called behavioral scores, which are simpler to derive and that are potentially more robust than metrics described in the previous research. Our major finding is that one of those scores, the Fixational Qualitative Score, has better sensitivity to eye fatigue than existing saccade-based metrics, in short-term range, while the task execution is in progress. Moreover, we hypothesize that the FQlS as a fixational metric can be effective when derived from a signal coming from the inexpensive eye trackers, therefore making it potentially applicable for employment on mobile and wearable devices with eye tracking capabilities.

Future work will concentrate on assessing if the achieved metric sensitivity to fatigue can be maintained on the low cost, low sampling frequency eye tracking equipment. Also we will search for other objective metrics with high sensitivity to eye fatigue and integrate them with FQlS and the best of saccade-based metrics in an application for mobile/wearable devices for next generation GUIs that are sensitive and adjustable to different levels of users' eye fatigue.

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