Human Operator Gaze Movement Characteristics Analysis for Fatigue Detection

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The paper investigates relationships between gaze movement characteristics and human fatigue. Gaze movement characteristics are calculated from such basic concepts of gaze as fixation and saccade. Characteristics can also be divided by the types of physical events on which they are based. It is possible to distinguish such characteristics as speed, time, quantity, size, percentage, frequency, and ratio characteristics. To search for correlations between gaze movement characteristics and fatigue, a dataset of gaze movements and the results of the VAS-F fatigue questionnaire were analyzed in 10 subjects. The dataset consists of operator parameters such as gaze movements, scene camera image, and gaze direction. To detect the level of fatigue, the participant completed the VAS-F questionnaire. Each record from the dataset corresponds to a questionnaire result. A total of 60 characteristics of eye movements and the corresponding VAS-F test values were analyzed and the correlation between them was calculated. The characteristics of eye movements were then sorted in descending order of the obtained correlation values. For further analysis, the first 20 characteristics with the highest correlation were selected from each participant. A search was then made for characteristics that were found in 60% or more of the participants among the first 20 characteristics. As a result, 9 characteristics of eye movements were found that correlated with VAS-F test scores for each participant. The significant correlation was shown by speed characteristics, size characteristics, time characteristics, frequency characteristics, ratio characteristics, and proportion characteristics.

I. Introduction

Decreased performance associated with fatigue is accompanied by loss of attention, slower reaction time, and an increase in the number of errors. Such errors often lead to catastrophic consequences in the work of air traffic controllers, operators of nuclear power plants, drivers of ships, airplanes, trains, cargo, public and personal vehicles. Early fatigue detection is a decisive factor in preventing accidents and catastrophic consequences. At the same time, operator support systems (Worker Assistance Systems) have become more and more popular in recent years [1].

Oculomotor events may be detectors of fatigue and sleepiness. All parameters related to fatigue detection can be divided into three groups: those related to saccades, blinks, and changes in pupil size. These parameters are uncontrollable by humans, and therefore are objective.

Saccades are fast ocular movements, generally occurring when the gaze is reoriented to a new target. Eye velocities are often above 500 degrees of visual angle per second, with an average duration between 20 and 40 ms [2]. On the other hand, fixations correspond to time intervals when the subject is looking at a particular point, usually an object of interest. Their duration typically range from 200 to 500ms, with an average around 300 ms [2].

The paper [3] says that peak saccade velocity, saccade duration, fixation duration, blink duration, blink rate, and pupil diameter may reflect changes in fatigue.

The paper [3] presents a study of fatigue in young and elderly people. The authors presented the following results: the frequency and duration of blinks increased with increasing time on task. In their opinion, changes in blink frequency are associated with changes in vigilance and level of attention. They associate changes in the duration of blinking with changes in the level of neuronal activation of blinking motor neurons and the orbicularis oculi muscle as fatigue progresses. In addition, when studying three types of fixation durations (<150 ms, 150–900 ms, >900 ms), the authors concluded that the duration of fixations of average duration increases due to fatigue. The range of changes in pupil diameter also increased during the task, as the force expended increased. The peak speed of saccades and their duration decrease as the experiment progresses.

It is noted in [4] that fixation eye movements (microsaccades and drift) and saccadic parameters can reliably indicate fatigue during long-term visual search, regardless of the complexity of the task.

In [5], the saccade was noted as a significant ocular event for the study of fatigue. In a two-hour virtual driving task simulation, the duration and peak velocity of saccades decreased with increasing task completion time. Peak saccade velocity decreased with increasing execution time in a computer task involving complex decision making [6] as well as in an air traffic control task [4]. In [7], it was shown that blinking is an informative ocular event that allows to detect fatigue. Blink duration and frequency were sensitive to changes in mental workload and degree of fatigue [8], [9]. Some studies [10], [11], [12], [13], [14] say about the connection between microsaccades and fatigue. The paper [15] says that the peak speed of saccades decreases as mental workload increases, which can be used to detect fatigue. In [1] demonstrated that mental workload and/or fatigue influence saccade dynamics and that peak saccade speed may be a suitable indicator of this relationship. The purpose of the paper is to search for gaze movement characteristics that have significant correlation with VAS-F test results.

II. Organization of the Paper

The first chapter describes existing methods of fatigue detection using eye movements from a literature review. The second chapter describes selected characteristics of eye movements and proposes a method for finding characteristics of gaze movements that correlate with fatigue. A search for correlations was performed, then the characteristics were sorted in descending order of correlation value and the first 20 characteristics were selected. Tables of eye movement characteristics with the highest correlation with VAS-F test scores for each participant are presented. An analysis was performed to see which types of eye movements were most correlated for each participant. The last chapter presents a summary table of the obtained characteristics with correlation values for each participant. An analysis was made of the characteristics that have the greatest correlation for all participants.

III. Eye Movement Dataset

The paper [16] describes an experimental setup for recording eye movements of a personal computer operator using an eye tracker. At the same time, operator parameters such as eye movements, scene camera image, and direction of gaze were calculated. To asses the degree of fatigue, the operator completed the VAS-F questionnaire. This questionnaire consists of 18 items regarding the subjective feeling of fatigue. For each item, the participant notes how they feel at the moment on a scale between two extremes (for example, from “not tired at all” to “extremely tired”).

To assess operator fatigue based on the eye movement strategy, gaze movement characteristics were calculated based on gaze coordinates at each time point. The eye movement data were analyzed to create two time series showing eye movements along x and y coordinates.

IV. Method for Eye Movement Characteristics Analysis

A method was developed to search for characteristics of eye movements that correlate with fatigue, presented in Fig. 1. This method consists of 4 stages: calculating the correlation between the characteristics of eye movements and the results of the VAS-F test, sorting the characteristics in descending order of the percentage of correlation, selecting the first 20 characteristics with maximum correlation, selection of characteristics present in 6 or more participants.

The selected 60 characteristics describe different types of eye movements. Among them we can distinguish such characteristics as speed, time, quantity, size, percentage, frequency, and ratio characteristics. The largest group consists of speed characteristics.

Speed characteristics reflect changes in the tracking characteristics of the gaze, and such speed characteristics as the average, minimum and maximum speed of gaze movement in degrees of visual angle per second were considered; module of average, minimum and maximum acceleration in degrees of visual angle per second2; average, minimum and maximum speed within the fixation area in degrees of visual angle per second, average, minimum and maximum saccade speed in degrees of visual angle per second, average, minimum and maximum instantaneous speed in degrees of visual angle per second.

Time characteristics such as the total duration of saccades in seconds, the average, minimum and maximum duration of a saccade in seconds, the duration of gaze fixations shorter than 150 ms, the duration of gaze fixations from 150 to 900 ms, the duration of gaze fixations from 900 ms are considered [1].

Quantitative characteristics were also considered: the number of saccades with an amplitude of less/more than 6 angular degrees, the number of gaze fixations shorter/longer than 180 ms, the number of gaze fixations shorter/longer than 180 ms per minute, the number of gaze fixations shorter than 150 ms per minute, the number of gaze fixations from 150 to 900 ms per minute, number of gaze fixations from 900 ms per minute. Size characteristics include such characteristics as average, minimum and maximum saccade length in angular degrees

The following percentage characteristics were considered: the proportion of gaze fixations shorter/longer than 180 ms, the proportion of gaze fixations shorter than 150 ms, the proportion of gaze fixations from 150 to 900 ms, the proportion of gaze fixations longer than 900 ms, the proportion of fixation time shorter than 150 ms, the proportion of gaze fixation time from 150 up to 900 ms, proportion of time of gaze fixation time from 900 ms.

Such frequency characteristics as the average, minimum and maximum frequency of the appearance of a new fixation area per second, the frequency of the appearance of a new fixation area for the entire time are considered. Such ratio characteristics as the average, minimum and maximum ratio of the path to the movement of the gaze are considered.

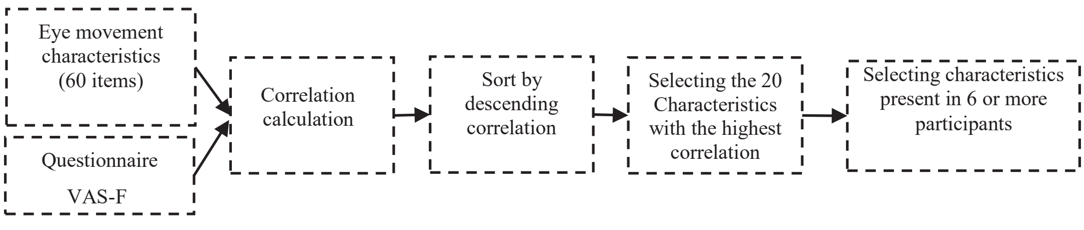

Fig. 1. Method for searching for characteristics of gaze movements that correlate with fatigue

Table I presents the characteristics of gaze movements and their correlation values with the VAS-F test scores for participant 1. The characteristics are sorted in descending order of correlation values and the top 20 characteristics with the highest correlation are presented.

As can be seen from the table, the highest correlations have speed characteristics such as minimum (58%) and maximum (50%) speed inside the fixation area, minimum speed of gaze movement in a second interval (50%), minimum gaze movement velocity (38%), maximum saccade speed (36%). Percentage characteristics as the proportion of fixations shorter (40%)/longer (40%) 180 ms, the proportion of time spent in fixations longer than 180 milliseconds (38%), the proportion of fixations shorter (38%)/longer (38%) 150 ms, the proportion fixations between 150 and 900 ms (38%), proportion of time spent in fixations longer than 150 milliseconds (37%), proportion of time spent in fixations between 150 and 900 milliseconds (37%). Next, correlations were calculated for participant 2. Table II presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test. As can be seen from the table, speed characteristics have the greatest correlation: maximum speed inside the fixation area (70%), average saccade speed (49%), maximum saccade speed (49%), minimum saccade speed (41%), minimum speed inside the fixation area (40%). Time characteristics such as maximum saccade duration (64%), minimum saccade duration (62%), average saccade duration (36%), total duration of fixations longer than 900 milliseconds (31%).

TABLE I. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 1

№	Characteristic name	Correlation value
1	Maximum saccade duration	61%
2	Minimum speed inside fixation area	58%
3	Maximum frequency of appearance of a new fixation area in a second interval	58%
4	Maximum saccade length	55%
5	Maximum speed inside fixation area	50%
6	Minimum speed of gaze movement in a second interval	50%
7	Proportion of fixations longer than 180 ms	40%
8	Proportion of fixations shorter than 180 ms	40%
9	Fixations longer than 900 ms per minute	39%
10	Minimum gaze movement velocity	38%
11	Proportion of time spent in fixations longer than 180 milliseconds	38%
12	Proportion of fixations longer than 150 ms	38%
13	Proportion of fixations shorter than 150 ms	38%
14	Proportion of fixations between 150 and 900 ms	38%
15	Minimum saccade length	37%
16	Proportion of time spent in fixations longer than 150 milliseconds	37%
17	Proportion of time spent in fixations between 150 and 900 milliseconds	37%
18	Maximum saccade speed	36%
19	Fixations longer than 150 ms, per minute	36%
20	Fixations shorter than 180 ms, per minute	36%

TABLE II. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 2

№	Characteristic name	Correlation value
1	Maximum speed inside fixation area	70%
2	Maximum saccade duration	64%
3	Minimum saccade duration	62%
4	Minimum saccade length	62%
5	Average saccade speed	49%
6	Maximum saccade speed	49%
7	Average path to gaze movement ratio	45%
8	Minimum saccade speed	41%
9	Maximum saccade length	40%
10	Minimum speed inside fixation area	40%
11	Proportion of fixations shorter than 150 ms	38%
12	Proportion of fixations longer than 150 ms	38%
13	Proportion of fixations longer than 180 ms	37%
14	Proportion of fixations shorter than 180 ms	37%
15	Average saccade duration	36%
16	Maximum path to gaze movement ratio	36%
17	Maximum instantaneous acceleration module	36%
18	Average saccade length	35%
19	The total duration of fixations is longer than 900 milliseconds	31%
20	Minimum path to gaze movement ratio	31%

Ratio characteristics as average path to gaze movement ratio (45%), maximum path to gaze movement ratio (36%), minimum path to gaze movement ratio (31%).

Next, correlations were calculated for participant 3. Table III presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

As can be seen from the table, the highest correlations have the following speed characteristics: minimum speed inside the fixation area (61%), maximum saccade speed (57%), maximum speed inside the fixation area (47%), minimum saccade speed (41%), minimum gaze movement speed in a second interval (32%), maximum speed of gaze movement in a second interval (29%). Ratio characteristics as the maximum ratio of path to gaze movement (69%), minimum ratio of path to gaze movement (41%). Percentage characteristics as the proportion of time spent in fixations shorter than 180 milliseconds, the proportion of time spent in fixations shorter than 150 milliseconds, the proportion of fixations shorter than 180 ms, the proportion of fixations longer than 180 ms.

Next, correlations were calculated for participant 4. Table IV presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

As can be seen from the table, the greatest correlation has quantitative characteristics such as fixations longer than 900 ms per minute (96%), fixations shorter than 150 ms per minute (96%), the number of saccades with an amplitude less than 6 angular degrees per minute (96%), fixations between 150 and 900 ms per minute (95%), false saccades per minute (95%), fixations longer than 150 ms per minute (94%), false fixations per minute (93%). Percentage characteristics as the proportion of time spent in fixations between 150 and 900 milliseconds (95%), the proportion of time spent in fixations shorter (91%)/longer (90%) 150 milliseconds, the proportion of time spent in fixations longer than 150 milliseconds (90%),

TABLE III. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 3

№	Characteristic name	Correlation value
1	Maximum path to gaze movement ratio	69%
2	Minimum speed inside fixation area	61%
3	Maximum saccade speed	57%
4	Maximum frequency of appearance of a new fixation area in a second interval	54%
5	Proportion of time spent in fixations shorter than 180 milliseconds	53%
6	Maximum speed inside fixation area	47%
7	Minimum saccade speed	41%
8	Minimum path to gaze movement ratio	41%
9	Maximum saccade duration	39%
10	Maximum saccade length	36%
11	Proportion of time spent in fixations shorter than 150 milliseconds	35%
12	False saccades per minute	34%
13	Average saccade duration	33%
14	Minimum speed of gaze movement in a second interval	32%
15	Minimum saccade length	31%
16	Maximum acceleration module in a second interval	31%
17	Minimum saccade duration	30%
18	Maximum speed of gaze movement in a second interval	29%
19	Proportion of fixations shorter than 180 ms	29%
20	Proportion of fixations longer than 180 ms	29%

TABLE IV. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 4

№	Characteristic name	Correlation value
1	Fixations longer than 900 ms per minute	96%
2	Fixations shorter than 150 ms per minute	96%
3	Number of saccades with amplitude less than 6 angular degrees per minute	96%
4	Proportion of time spent in fixations between 150 and 900 milliseconds	95%
5	Fixations between 150 and 900 ms per minute	95%
6	False saccades per minute	95%
7	Frequency of appearance of a new fixation area	95%
8	Average frequency of appearance of a new fixation area in a second interval	95%
9	Fixations longer than 150 ms per minute	94%
10	Minimum speed inside fixation area	94%
11	Average speed inside the fixation area	93%
12	False fixations per minute	93%
13	Minimum speed of gaze movement in a second interval	91%
14	Average saccade duration	91%
15	Proportion of time spent in fixations shorter than 150 milliseconds	91%
16	Maximum saccade duration	90%
17	Proportion of time spent in fixations longer than 150 milliseconds	90%
18	Proportion of time spent in fixations shorter than 180 milliseconds	90%
19	Proportion of fixations shorter than 150 ms	90%
20	Proportion of fixations longer than 150 ms	90%

proportion of time spent in fixations shorter than 180 milliseconds (90%), proportion of fixations shorter than 150 ms (90%). Next, correlations were calculated for participant 5. Table V presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

As can be seen from the table, the highest correlations have the following speed characteristics: minimum saccade speed (45%), average speed inside the fixation area (41%), minimum speed inside the fixation area (36%), maximum gaze movement velocity (34%), maximum speed saccades (34%), maximum speed of gaze movement in a second interval (33%), minimum gaze movement velocity (25%). Quantitative characteristics as false saccades per minute (36%), fixations shorter than 150 ms per minute (33%), fixations shorter than 180 ms per minute (31%), fixations between 150 and 900 ms per minute (28%).

Next, correlations were calculated for participant 6. Table VI presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

As can be seen from the table, the highest correlations have speed characteristics such as maximum saccade speed (60%), minimum saccade speed (47%), maximum gaze movement velocity (47%), maximum speed inside the fixation area (45%).

Ratio characteristics as average path to gaze movement ratio (52%), maximum path to gaze movement ratio (47%). Time characteristics such as maximum saccade duration (48%), total duration of fixations longer than 900 milliseconds (47%), minimum saccade duration (42%).

Next, correlations were calculated for participant 7. Table VII presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

TABLE V. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 5

№	Characteristic name	Correlation value
1	Maximum acceleration module in a second interval	49%
2	Minimum saccade speed	45%
3	Minimum saccade length	44%
4	Average speed inside the fixation area	41%
5	False saccades per minute	36%
6	Minimum speed inside fixation area	36%
7	The total duration of fixations is longer than 900 milliseconds	36%
8	Maximum gaze movement velocity	34%
9	Maximum saccade speed	34%
10	Maximum speed of gaze movement in a second interval	33%
11	Fixations shorter than 150 ms per minute	33%
12	Maximum saccade duration	32%
13	Proportion of time spent in fixations shorter than 150 milliseconds	31%
14	Fixations shorter than 180 ms per minute	31%
15	Proportion of time spent in fixations shorter than 180 milliseconds	30%
16	Number of saccades with amplitude less than 6 angular degrees per minute	30%
17	Frequency of appearance of a new fixation area	29%
18	Fixations between 150 and 900 ms per minute	28%
19	Minimum gaze movement velocity	25%
20	Maximum frequency of appearance of a new fixation area in a second interval	25%

TABLE VI. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 6

№	Characteristic name	Correlation value
1	Maximum saccade speed	60%
2	Average path to gaze movement ratio	52%
3	Proportion of fixations between 150 and 900 ms	51%
4	Maximum frequency of appearance of a new fixation area in a second interval	50%
5	Maximum saccade duration	48%
6	Minimum saccade speed	47%
7	The total duration of fixations is longer than 900 milliseconds	47%
8	Maximum path to gaze movement ratio	47%
9	Maximum gaze movement velocity	47%
10	Proportion of fixations longer than 150 ms	45%
11	Proportion of fixations shorter than 150 ms	45%
12	Maximum speed inside fixation area	45%
13	Minimum saccade length	42%
14	Minimum saccade duration	42%
15	Proportion of fixations longer than 900 ms	41%
16	Proportion of time spent in fixations longer than 900 milliseconds	39%
17	Module of average acceleration in a second interval	39%
18	Fixations longer than 180 ms per minute	39%
19	False fixations per minute	38%
20	Maximum saccade length	38%

As can be seen from the table, the highest correlations have the following speed characteristics: maximum speed inside fixation area (84%), maximum saccade speed (61%), average instantaneous acceleration module (52%), module of average acceleration in a second interval (50%), average saccade speed (49%), minimum speed inside fixation area (47%). Ratio characteristics as the maximum ratio of path to gaze movement (73%), minimum ratio of path to gaze movement (67%). Percentage characteristics as the proportion of time spent in fixations shorter than 180 milliseconds (57%), the proportion of time spent in fixations longer than 150 milliseconds (54%), the proportion of fixations shorter than 180 ms (48%).

Next, correlations were calculated for participant 8. Table VIII presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

As can be seen from the table, the highest correlations have the following speed characteristics: maximum saccade speed (75%), minimum speed of gaze movement in a second interval (72%), maximum speed inside fixation area (71%), average saccade speed (71%), maximum gaze movement velocity (56%). Time characteristics as maximum saccade duration (76%), average saccade duration (63%), minimum saccade duration (50%), the total duration of fixations is longer than 900 milliseconds (50%). Percentage characteristics as the proportion of fixations between 150 and 900 ms (57%), proportion of fixations longer than 150 ms (54%), proportion of fixations longer than 180 ms (54%), proportion of fixations shorter than 180 ms (51%), proportion of fixations shorter than 150 ms (51%).

Next, correlations were calculated for participant 9. Table IX presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

TABLE VII. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 7

№	Characteristic name	Correlation value
1	Maximum speed inside fixation area	84%
2	Maximum path to gaze movement ratio	73%
3	Minimum path to gaze movement ratio	67%
4	Maximum saccade speed	61%
5	Maximum saccade duration	60%
6	Proportion of time spent in fixations longer than 180 milliseconds	57%
7	False fixations per minute	55%
8	Proportion of time spent in fixations longer than 150 milliseconds	54%
9	Average instantaneous acceleration module	52%
10	Maximum saccade length	52%
11	Module of average acceleration in a second interval	50%
12	Average saccade speed	49%
13	Proportion of time spent in fixations shorter than 180 milliseconds	48%
14	Minimum speed inside fixation area	47%
15	Maximum instantaneous acceleration module	47%
16	Maximum gaze movement velocity	47%
17	Average speed of gaze movement in a second interval	44%
18	Average eye movement velocity	44%
19	Fixations shorter than 150 ms per minute	43%
20	Fixations between 150 and 900 ms per minute	42%

TABLE VIII. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 8

№	Characteristic name	Correlation value
1	Maximum saccade duration	76%
2	Maximum saccade speed	75%
3	Maximum saccade length	74%
4	Minimum speed of gaze movement in a second interval	72%
5	Maximum speed inside fixation area	71%
6	Average saccade speed	71%
7	Maximum frequency of appearance of a new fixation area in a second interval	71%
8	Average saccade length	70%
9	Average saccade duration	63%
10	Maximum path to gaze movement ratio	60%
11	Proportion of fixations between 150 and 900 ms	57%
12	Maximum gaze movement velocity	56%
13	Proportion of fixations longer than 150 ms	54%
14	Proportion of fixations longer than 180 ms	54%
15	Maximum speed of gaze movement in a second interval	52%
16	Proportion of fixations shorter than 180 ms	51%
17	Proportion of fixations shorter than 150 ms	51%
18	Minimum saccade duration	50%
19	The total duration of fixations is longer than 900 milliseconds	50%
20	Minimum speed inside fixation area	49%

As can be seen from the table, the highest correlations have the following speed characteristics: minimum speed inside fixation area (60%), maximum saccade speed (60%), Average saccade speed (52%), maximum speed inside fixation area (48%). Time characteristics as total duration of fixations is longer than 900 milliseconds (55%), maximum saccade duration (54%), the total duration of fixations is shorter than 180 milliseconds (51%), the total duration of fixations is shorter than 150 milliseconds (51%), the total duration of fixations is between 150 and 900 ms (50%), total duration of fixations is longer than 150 milliseconds (50%), total duration of fixations is longer than 180 milliseconds (49%). Percentage characteristics as proportion of fixations longer than 180 ms (52%), proportion of fixations shorter than 180 ms (52%), proportion of fixations longer than 150 ms (48%).

Next, correlations were calculated for participant 10. Table X presents the characteristics of eye movements and the values of their correlation with the values of the VAS-F test.

As can be seen from the table, the highest correlations have the following speed characteristics: maximum speed inside fixation area (78%), average saccade speed (76%), maximum saccade speed (67%), average acceleration module in a second interval (64%), minimum speed inside fixation area (59%), average instantaneous acceleration module (39%). Time characteristics as average saccade duration (84%), minimum saccade duration (58%), maximum saccade duration (42%). Size characteristics as average saccade length (80%), maximum saccade length (55%), minimum saccade length (41%).

V. CONCLUSION

As a result of the research presented in the paper 9 characteristics were found, which are presented in Table XI. These characteristics were found in 60% or more of the participants among the first 20 characteristics and, therefore, have a correlation with fatigue.

TABLE IX. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 9

№	Characteristic name	Correlation value
1	Maximum frequency of appearance of a new fixation area in a second interval	71%
2	Minimum path to gaze movement ratio	61%
3	Minimum speed inside fixation area	60%
4	Maximum saccade speed	60%
5	Fixations longer than 180 ms per minute	56%
6	Total duration of fixations is longer than 900 milliseconds	55%
7	Maximum saccade duration	54%
8	Maximum saccade length	54%
9	Maximum path to gaze movement ratio	53%
10	Average saccade speed	52%
11	Average saccade length	52%
12	Proportion of fixations longer than 180 ms	52%
13	Proportion of fixations shorter than 180 ms	52%
14	Total duration of fixations is shorter than 180 milliseconds	51%
15	Total duration of fixations is shorter than 150 milliseconds	51%
16	Total duration of fixations is between 150 and 900 ms	50%
17	Total duration of fixations is longer than 150 milliseconds	50%
18	Total duration of fixations is longer than 180 milliseconds	49%
19	Maximum speed inside fixation area	48%
20	Proportion of fixations longer than 150 ms	48%

TABLE X. CORRELATION OF GAZE MOVEMENT CHARACTERISTICS WITH VAS-F RESULTS OF PARTICIPANT 10

№	Characteristic name	Correlation value
1	Average saccade duration	84%
2	Average saccade length	80%
3	Maximum speed inside fixation area	78%
4	Average saccade speed	76%
5	Maximum path to gaze movement ratio	75%
6	False fixations per minute	71%
7	Maximum saccade speed	67%
8	Average acceleration module in a second interval	64%
9	Average path to gaze movement ratio	60%
10	Minimum speed inside fixation area	59%
11	Minimum saccade duration	58%
12	Maximum saccade length	55%
13	Proportion of time spent in fixations longer than 150 milliseconds	52%
14	Proportion of time spent in fixations longer than 180 milliseconds	52%
15	Number of saccades with amplitude more than 6 angular degrees per minute	45%
16	Maximum saccade duration	42%
17	Minimum saccade length	41%
18	Average frequency of appearance of a new fixation area in a second interval	41%
19	Fixations between 150 and 900 ms per minute	39%
20	Average instantaneous acceleration module	39%

As can be seen from the table, the mostly speed characteristics were found, namely minimum/maximum speed inside fixation area, maximum saccade speed. Two size characteristics was found as minimum/maximum saccade length. One time characteristic was found as maximum saccade duration. The hypotheses [1], [3], [5], [15] about the connection with fatigue of the dynamics of saccades: duration, speed, peak speed were confirmed. One frequency characteristic was found as maximum frequency of appearance of a new fixation area in a second interval. One characteristic of the ratio as was found as maximum path to gaze movement ratio. Finally, one percentage characteristic was found as proportion of fixations longer than 150 ms. As a result of the analysis, it turned out that speed characteristics associated with fixation areas and saccades have the biggest correlation with fatigue. Size characteristics are also associated with fixation areas and saccades. The proportion of fixations longer than 150 ms correlates with fatigue and corresponds to the assumption above [3]. Time and frequency characteristics are also associated with the area of fixation and saccades.

For the future work we plan to increase the number of participants to obtain characteristics of eye movements that most accurately correlate with fatigue. It is also planned to add other methods for fatigue detection for a more objective result.

TABLE XI. FOUND CHARACTERISTICS AND THEIR CORRELATION VALUES WITH VAS-F RESULTS FOR ALL PARTICIPANTS

№	Characteristic name	Maximum correlation value									
		1	2	3	4	5	6	7	8	9	10
1	Maximum saccade duration	61%	64%	39%	90%	32%	48%	60%	76%	54%	42%
2	Minimum speed inside fixation area	58%	40%	61%	94%	36%	38%	47%	49%	60%	59%
3	Maximum frequency of appearance of a new fixation area in a second interval	58%	30%	54%	76%	25%	50%	39%	71%	71%	28%
4	Maximum saccade length	55%	40%	36%	78%	21%	38%	52%	74%	54%	55%
5	Maximum speed inside fixation area	50%	40%	61%	62%	36%	45%	84%	71%	60%	59%
6	Minimum saccade length	37%	62%	31%	86%	44%	42%	38%	48%	47%	41%
7	Maximum saccade speed	36%	49%	57%	64%	34%	60%	61%	75%	60%	67%
8	Maximum path to gaze movement ratio	33%	36%	69%	44%	20%	47%	73%	60%	53%	75%
9	Proportion of fixations longer than 150 ms	38%	38%	28%	90%	24%	45%	25%	54%	48%	23%

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