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Oculomotor reactions in fixations and saccades with visual perception of information

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Abstract. The work is devoted to the peculiarities of gaze movement in fixations and saccades when reading text and perceiving neutral images. The existence of multiple (almost unidirectional) displacements in fixations was discovered, the probability of which significantly exceeds the similar probability in simulated random fixations. The dependence of the correlation of time spent in fixations on the degree of distortion of texts when reading them was investigated. An interesting aspect of research is the statistics of the distribution of the direction of gaze shifts in fixations and saccades. It is shown that during reading the direction of displacements in saccades is predetermined. In the case of fixations in the distribution, vertical and horizontal directions are distinguished, and this is typical not only when reading a text, but also when perceiving various images, including those rotated at different angles. The individual characteristics of the visual system associated with the non-synchronous movement of the gaze of the left and right eyes in some subjects were found. It was determined the noise error of the eye-tracking recording system when registering the gaze displacements. It is shown that down to gaze displacements of the order of 1 mm, the noises of the registering measurement system prevails, which have a normal distribution along the length, and are uniformly distributed over the angle.

Keywords: oculomotor reactions (oculomotorics), technology of eye tracking, fixations, saccades, reading text, multiple shifts

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"Vultus est index animi"
("Eyes are the soul mirror")
Mark Thullius Cicero.

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1. INTRODUCTION

Studies of eye movement in the visual perception of various information are intensively conducted to solve a number of physiological and psychological problems. Each person has a structure of lines, dots and colors in the eye iris combined in unique combinations. Some people may have similar eye color, but the lines and dots on the iris themselves are as unique as fingerprints. It is known that almost everything can be determined at a person's eyes: his mood, character traits, truthfulness of words and many other aspects of his inner world. An analysis of the involuntary eyes reaction to information can tell a lot not only about the individual physiological characteristics of the human visual apparatus, but also about the cognitive and psychological characteristics of the individual, his preferences, positive and negative emotions caused by information, about of hidden and suppressed feelings and emotions.

Recently, another important aspect of research in this area has appeared - the effect of oculomotor reactions on visual acuity [1]. High visual acuity is extremely important in various life situations and for many professional tasks, from confident recognition of objects to driving cars and airplanes. It is well known that the optical and anatomical characteristics of the eye contribute to good vision and

spatial resolution, but the effect of reflex eye movements on improving visual acuity has not been studied. Thus, the study of oculomotor activity in the perception of information is quite an urgent task.

2. EQUIPMENT AND RESEARCH METHODS

The eye movement trajectory during visual perception of information consists mainly of local fixations, when the gaze is fixed in the area of individual image elements, and saccades, when the gaze is transferred from one element to another. If the eyes movement in saccades is more less obvious and understandable, then in the fixations the situation is much more complicated, both in terms of the time spent by the gaze in them, and in terms of the gaze trajectory [2]. With visual perception of information of the order of 90% of the time, the gaze is in fixations and, apparently, at this time the formation and cognitive awareness of the visual pattern by the human brain occurs.

The intensity of this activity is far from always the same and strongly depends on the nature of the presented images. For example, at reading of familiar signs (letters, numbers, and other signs) are perceived almost automatically (at a reflex level), it does not require a long examination, and it remains only to understand the text and follow the content of what is read. With a general perception of graphical information (pictures, figures) with neutral content, in the absence of fine details or a masked image in them, the pattern of eye movement is very different from the pattern when reading and consists practically of only saccades.

In this work, eye movement was register using a computer installation with eye tracking technology iView X™ High Speed 1250 IT from the German company SMI GmbH

(resolution $< 0.01^\circ$, sampling frequency 1250 Hz). In the experiment, the observer's head is located at a certain distance from the monitor screen (80 cm), on which the desired image is presented, and in order to avoid involuntary movements and turns, it is fixed in a special device. The installation works in the "dark pupil" mode. Herewith, the eye is illuminated by a point source of infrared radiation, and the infrared video camera performs high-speed shooting of the eye. In the image, the position of the pupil is determined programmatically (in IR rays it is a dark oval) and its size, as well as the position of the corneal flare, which is a reflection on the cornea of an infrared light source. In the image, the position of the pupil and its size are determined programmatically (in IR rays it is a dark oval), as well as the position of the corneal light patch, which is a reflection on the cornea of an infrared light source. The direction of gaze is calculated based on a vector connecting the positions of the corneal light patch and the center of the pupil. The power level of the IR source is sufficient for experiments, but does not exceed the value dangerous to the eye. The parameters of the infrared eye image after processing by a special computer program are saved in the data file.

Before starting measurements in the calibration process, the deviation of the observer's pupil from its central position is determined on the system of special reference points on the monitor screen. On the developed algorithm, the relationship between the position of the pupil and the position on the monitor screen of the observer's gaze on the image is determined. As a result of using this algorithm, we can track on the monitor screen a gaze at the image, rather than eye movement.

Of the several possible types of eye movement, differing in temporal and spatial

characteristics, three basic characteristics of eye movement were registering at the setup when observing the image: saccades, fixations, and the pattern of eye movements formed by the successive selections from fixations and saccades. The trajectories of displaying the movement of the gaze were constructed by connecting the points with time-successive coordinates, determined by the sampling frequency of the digital measuring system.

For the study of involuntary eye movements that are not related to cognitive processes in the brain, two types of gaze displacements are of interest: microsaccades (fixations) - short displacements with a sharp change in direction associated with the process of accommodation of the visual apparatus, and relatively longer saccades associated with gaze transfer to another place and having an average of approximately one direction [4,5].

A pattern of eye movement image in the fixations area is a multiplicity of closely and randomly located points on which the gaze passes sequentially. Herewith a comparative statistical analysis of the points distribution in the fixation region is of interest. A comparative model for the pattern of eye movement image in the fixations region can be the random distribution with specified parameters (size of the fixation region, dispersion and approximately the same points density over the entire fixation area, average displacement). Thus, if using the random number generator we create an artificial "random" fixation (CF) with the necessary parameters, then its statistical characteristics and some parameters can serve as if standards when comparing with similar characteristics of real fixations (RF). The evident differences in these characteristics, that are detected, are likely to be due to cognitive processes in the brain.

The gaze movement in the fixation area is also characterized by the temporary distribution

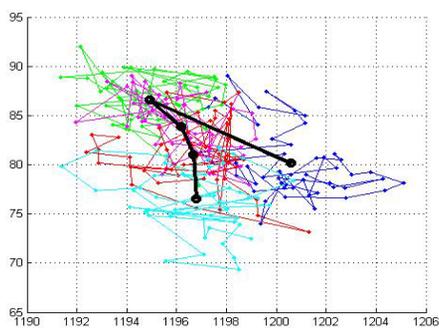


Fig. 1. Sequential fragments of fixation (shown in color) with a length of 50 points. The centers of gravity of fragments drift along a thick solid line.

of points in it. If the RF is divided into separate fragments and the position of the center of gravity is determined for each fragment, then connecting them with a solid line, it turns out that the centers of fragments gravity as if drift along the whole fixation, further complicating the creation of the SF model (**Fig. 1**).

From general considerations, the movement of the gaze in fixations should provide the solution of two problems: retention of the image of some moment considered image element in the fovea region (the central area of the retina is the region of the highest density of cones) and ensuring the absence of the effect of receptors saturation [6].

The experiment involved several testees aged 20 to 65 years. Let us conditionally denote them by the letters E, O, V, M, Z, P4, P5 and P7. The first five were asked to view, for no specific task, for 10 seconds, three neutral images **Fig. 1a,b,c** (we will conditionally denote them by F, T, and W), which at each subsequent observation turned 45° relative to the previous position, moreover, in testees M and Z the



Fig. 1a,b,c. Images of various structures presented in the experiment: a - "fractal" (F); b - "tree" (T) and c - "wave" (W).

coordinates of both the left and right gaze were registering, but with a frequency $f = 500$ Hz.

Testees P4, P5, and P7 were asked to read 11 short texts (3-4 lines), herewith the first version of each text fully corresponded of orthography, while the reading of the next five versions of the same text was deliberately complicated by distortions: punctuation marks and gaps between words were excluded, extra spaces were inserted, the letters in the words changed places and at the same time the words were rearranged or torn.

3. ANALYSIS OF THE GLANCE MOVEMENTS TRAJECTORY IN THE FIELD FIXATIONS AREA

For the CF model, the probability of implementation of several approximately unidirectional consecutive displacements (hereinafter referred to as multiple displacements, moreover by the displacement multiplicity k , we mean the number of consecutive, unidirectional displacements) should decrease sharply with increasing multiplicity k . The experimental data show that the number of such multiple displacements in real fixations (RF) always exceeds the analogous number for CF at the identical statistics (full number of displacements in fixation). The procedure for detecting multiple displacements in the RF is as follows: when the RF length is equal to N , the sums of the lengths of k successive displacements were calculated (obviously such sums were accumulated $(N-k+1)$), then from the each thus obtained sum was deducted the length of displacement from the beginning of the first displacements to end of k -th. If the obtained difference turned out to be less than a tenth of the average displacement length in the RF, then it was believed that the data of k displacements have approximately the same

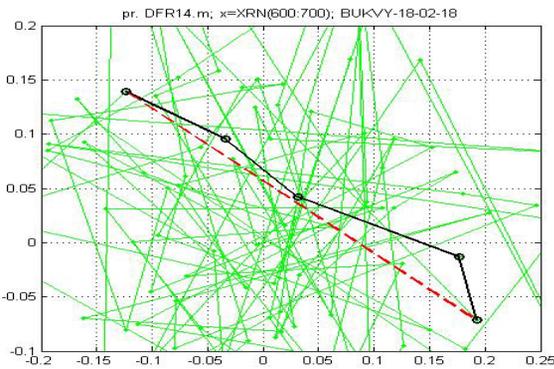


Fig. 2. A fragment of real tracking, in which 4 consecutive displacements made in approximately the same direction and a dashed line highlighting the movement between the start and end points of the track are highlighted in a bold line.

direction, otherwise these k displacements were not considered unidirectional.

The described procedure for the multiplicity $k = 4$ is illustrated in **Fig. 2**. In fact, the resulting displacement along k segments of the broken line is compared with the sum of the lengths of the same segments elongated along a straight line (in one direction). Note that one tenth of the average displacement length is of the order of 0.04-0.2 mm and is a rather hard selection criterion.

In total, more than 103 fixations of various lengths were processed. The processing results are presented in graphs (**Fig. 3a** and **3b**), showing the ratio of the multiple displacements number to the total displacements number depending on the multiplicity k . In the same axes, a similar

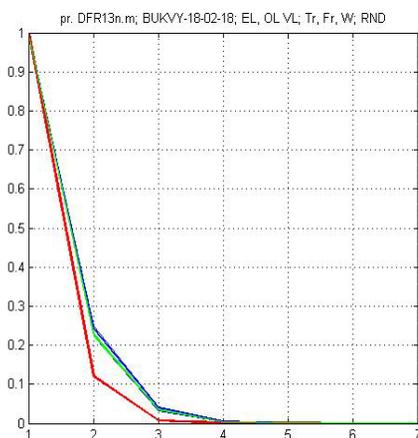


Fig. 3a. Dependence of the fraction of multiple displacements on the multiplicity k (the red curve for the CF is the rest for the RF).

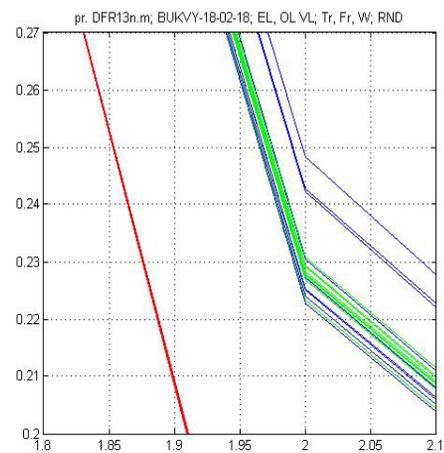


Fig. 3b. Dependence of the fraction of multiple displacements on the multiplicity k (the red curve for the CF is the rest for the RF).

relation was constructed for artificial random fixation of the CF, which was generated so that the average displacement length in it was the same as in the RF, and the number of points coincided exactly.

The appearance of the CF and RF graphs is exactly the same, the multiple displacements number in the CF for any multiplicity is always less than in real ones, and for multiplicity $k > 4$ they are completely absent (the fixation contains about 50,000 points), while in real fixations there are displacements, the multiplicity of which reaches 7 even with a shorter duration.

At the same time, a very small scatter in the values (graphs practically merge) of the indicated dependences for real fixations, irrespective of the testee and the object under consideration, attracts attention.

Of particular note is the fact that these dependencies for real fixations have a very small spread in values (the graphs practically merge), regardless of the testee and the object under consideration. Apparently, this indicates that the mechanism (algorithm) of eye movement in fixations is identical in all testees. Given the temporal characteristics of movement, we can assume the presence of a specific video processor (apparently located in

the brain), which should be as close as possible to the muscles performing these movements [6]. Based on the experimental data, a search was carried out for possible preferred directions with multiple displacements in the fixation region. Since we know the starting and ending points of displacements, depending on which one is closer to the center of fixation, one could be judge a certain preferred direction of multiple displacements and draw conclusions about their purpose. However, the analysis of the tracks showed that such a predominant direction does not exist, up to a multiplicity of $k = 4$, with large multiples a certain difference appears, but it is not provided statistically, the angular distributions of multiple displacements do not reveal any the peculiarities.

4. EYE MOVEMENT ANALYSIS WHEN READING TEXTS

Obviously, when reading texts, the gaze movement is strictly determined. This fact is easily confirmed by numerous gaze tracking, which easily recognizes the movement along the lines, with a certain number of stops in fixations, saccade movement between words and return saccades, returning the gaze to the beginning of the next line [5,6]. Herewith, the gaze spends the same 90% of the time in fixations and, apparently, at this time the reading and preliminary comprehension of what is read takes place. The idea of the experiment described below was to make the look spend more time in fixations, artificially complicating the process of reading and perceiving the text, distorting it in a certain way. How this is done can be illustrated by the example of one of 11 texts. First, we give the source text and 5 distorted versions of it.

1) any point that is estimated to be located at the same distance from the eyes as the fixation point forms two projections of the corresponding points of the retinas,

2) any point that is estimated to be located at the same distance from the eyes as the fixation point forms two projections of the corresponding points of the retinas,

3) any point that is estimated to be located at the same distance from the eyes as the fixation point forms two projections of the corresponding points of the retinas,

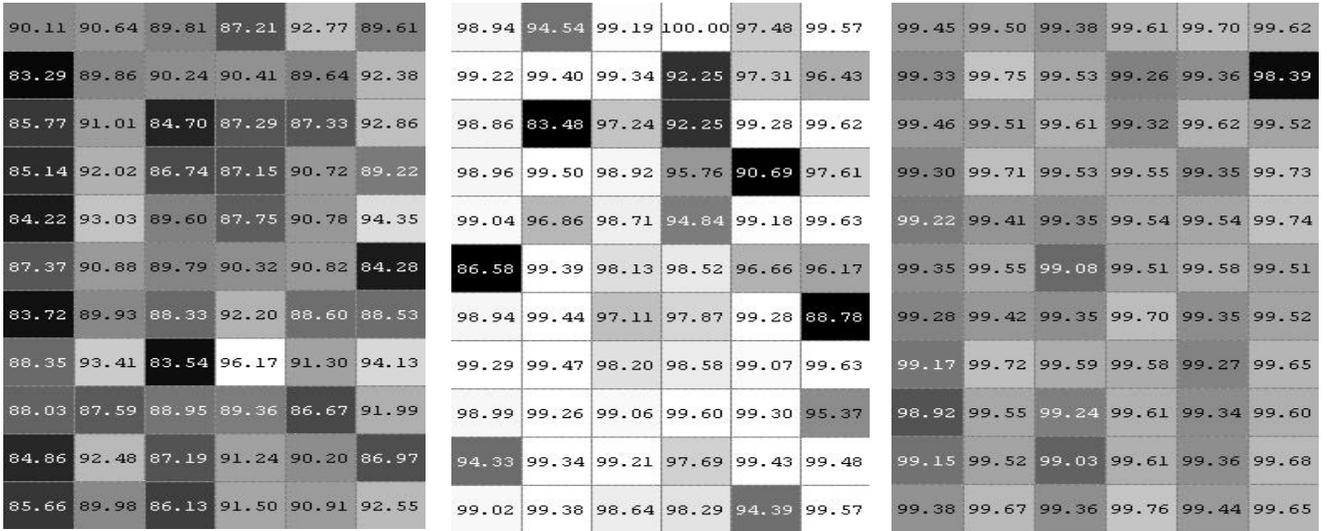
4) any point that is estimated to be located at the same distance from the eyes as the fixation point forms two projections of the corresponding points of the retinas,

5) any point that is estimated to be located at the same distance from the eyes as the fixation point forms two projections of the corresponding points of the retinas,

6) any point that is estimated to be located at the same distance from the eyes as the fixation point forms two projections of the corresponding points of the retinas.

At first glance, the above examples show that the perception of distorted texts is significantly more difficult compared to undistorted ones and, accordingly, the time spent in fixations should increase, because Saccades do not seem to require such an increase in time. Let us denote the ratio of the time spent in fixations to the total time spent reading text through $F_k(i,j)$, where k is the index belonging to a particular testee, i is the text number, j is the variant of its distortion. The calculation results are shown in **Fig. 4a,b,c**, in the form of corresponding matrices of size (11×6) , where each element of the matrix is a ratio of time $F_k(i,j)$, expressed as a percentage.

Unfortunately, to make some unambiguous conclusion from the data in Fig. 4. quite difficult. Only testee F_4 spent the least time reading all eleven versions of the undistorted text. In testees F_5 and F_7 , this conclusion was not confirmed.



a) F_4 (testee no.4) b) F_5 (testee no. 5) c) F_7 (testee no. 7)

Fig. 4. Tables of the ratio of the time $F_k(i, j)$ spent in fixations to the total time spent reading the text.

5. ANGULAR DISTRIBUTIONS OF DISPLACEMENTS IN FIXATIONS AND SAKKADES

Along with the study of approximately unidirectional, sequential displacements of the gaze movement in the fixations and saccades, it is also important to study the angles at which individual displacements are made for times $t = 0.8$ ms or $t = 2.0$ ms, depending on the frequency, with which the gaze position was recorded. For each displacement, the angle at which it occurred was calculated, and the angle was counted counterclockwise from the horizontal axis. The angles were calculated separately for displacements belonging to fixations, saccades, or the whole tracking, herewith the belonging of each point to a fixation or saccade was determined in a standard way programmatically and displayed as the corresponding attribute in the data file. Ultimately, angular displacement distributions were constructed in polar or Cartesian coordinates.

Typical distributions in Cartesian coordinates are shown in Fig. 5. It should be noted that the size of the fixation region is usually small, its area is about 1–100 mm², and, as a rule, the entire fixation is completely projected onto the retina fovea region. In

this case, the fixation area is the area of a rectangle located in the plane of the monitor and having an angular size of the order of one degree and the lengths of the sides of which are determined by the extreme coordinates of the fixation points along the corresponding axes.

A certain spread of points belonging to the fixation can be determined by the noises of the recording system. But if the noises of the system played an overwhelming role, then the displacements angular distribution in polar coordinates would be an almost strict circle, which is quite easily verified using a random number generator in the corresponding CF model. However, all angular distributions for displacements in real fixations and

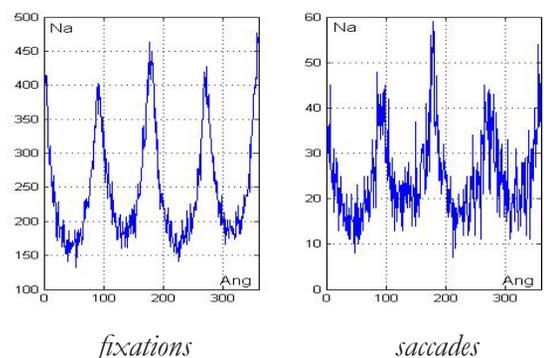


Fig. 5. Integral (total) angular distributions for fixations and saccades (testee E, 8 image positions T). About 200 fixations and saccades were studied.

saccades show obvious deviations from the circumference, and this statement is true for fixations and saccades of any duration. The characteristic signs of asymmetry are manifested in distributions for virtually every fixation. To a lesser extent, the above statement refers to saccades because of significantly less statistics.

Similar distributions take place for all testees; asymmetry, expressed to a greater or lesser extent is clearly present in all angular distributions.

The perception of rotated images observed by subjects M and Z was also studied, herewith the coordinates of the gaze for the left and right eyes were recorded simultaneously. Corresponding angular distributions are presented in **Fig. 6**, from which it is obvious that the distributions of testee Z are almost the same, while for M they are slightly different, and the difference is manifested for any orientation of the image, which is apparently due to some individual characteristics of the visual apparatus.

It is noteworthy that the asymmetry of the angular distribution of the direction of displacements when observing neutral images for saccades is almost the same as for fixations. A completely different situation is observed when the eye movement is predetermined to be rigidly determined (for example, reading). In **Fig. 7** shows the angular distribution of displacements in all saccades that arise when the

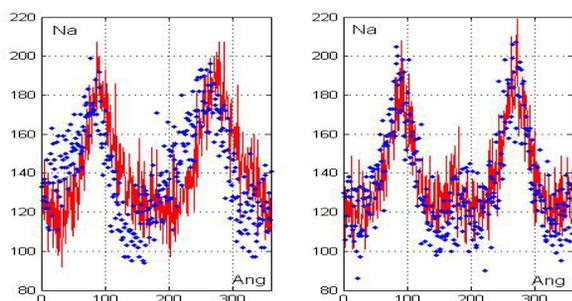


Fig. 6. Angular distributions for fixations (testee M - on the left, Z - on the right).

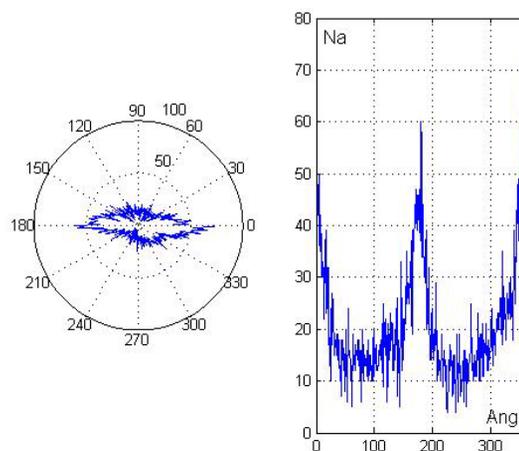


Fig. 7. Angular distributions for all saccades that arise when the testee P reads six variants of the second text (7598 points in total).

testee P reads six variants of the second text. The asymmetry clearly changed in a completely predictable way, the angular distribution in the fixations practically remained the same.

We also studied the change in the direction of gaze movement during the implementation of two successive displacements. Obviously, this change is determined by the difference in the angles of directions of the two indicated displacement. If the angles for the displacements vary from 1° to 360° , then the difference of these angles will take values from -359° to $+359^\circ$.

For comparison, we consider a model of artificial random fixation (CF), for which the angular distribution of the gaze displacements direction will be uniform, and in polar coordinates it will be a circumference. For such a model fixation, the rotation angles of the displacements are determined as the difference when subtracting the previous angle from the subsequent angle. The angular distribution of such rotation angles (or deviation) is shown in **Fig. 8**. The same distribution is given there for real fixations (RF) of testee E, taking into account all image orientations T (AgW1eIT). The number of points in the CF and the RF is taken so that the statistics are the same (88,615 points).

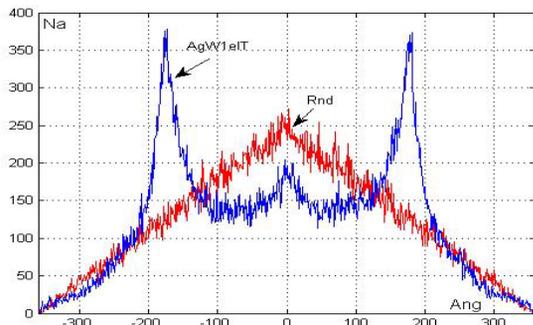


Fig. 8. Angular distributions for the angles of deviation of the "ideal" fixation (Rnd), for all fixations of the test E taking into account all the orientations of the image T (AgW1eIT).

The fundamental difference between one distribution and another one is obvious.

Moreover, the distribution for "perfect" fixation (CF) remains unchanged, if by the angle of rotation we mean the angle between any pair of displacements. For real fixations (RF), this statement is false, which is shown in **Fig. 9**, which shows the distributions for the rotation angles of displacements whose ordinal numbers differ by 1 (AgW1eIT) and 2 (AgW2eIT). With increasing difference in ordinal numbers, the distribution strives for Rnd in Fig. 8 for CF. Apparently, such a difference in the distribution of real fixations from "purely random" ones indicates a certain correlation of the nearest two or four gaze displacements, which is completely absent in the random process.

The angular distribution for the displacements in the fixations, presented

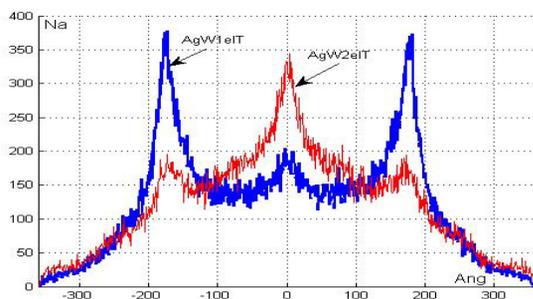


Fig. 9. Distributions for rotation angles of displacements whose ordinal numbers differ by 1 (AgW1eIT) and 2 (AgW2eIT).

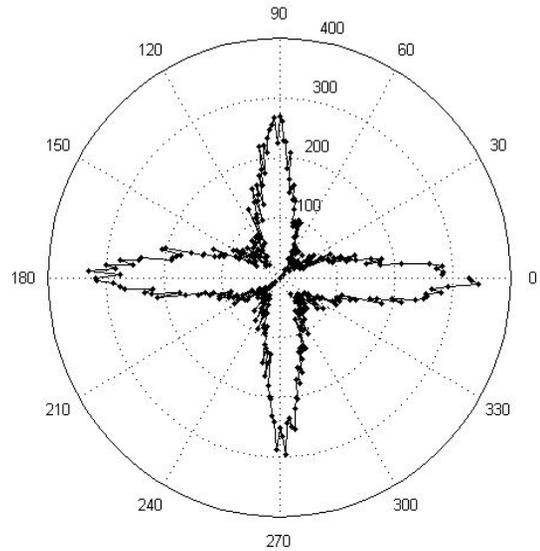


Fig. 10. The corrected angular distribution of AgFET-132.

in Fig. 5 includes purely noise offsets, the distribution of which is an almost strict circumference. If we take the radius of such a circumference equal to the minimum value in the full distribution (in the indicated case, this value is 132) and exclude it from the full distribution, then we can obtain the angular distribution of real gaze displacements, which is presented in **Fig. 10**.

The distribution clearly shows the predominance of vertical and horizontal directions in the angular distributions of displacements in fixations and saccades. This is possibly due to the natural coordinate system in the perception of visual information associated with the horizon line and vertical direction (gravity direction).

6. ANALYSIS INFLUENCE OF NOISES OF RECORDING EQUIPMENT

The distribution (Fig. 10) clearly shows the predominance of vertical and horizontal directions in the angular distributions of displacements in fixations and saccades, which is apparently associated with the system of oculomotor muscles. The oculomotor muscles help to carry out the coordinated

movement of the eyeballs, and also, in parallel, provide a high-quality perception of visual information. The motor function of the eye is provided by six muscles - four of them are straight, and two are oblique. Their names are associated with the peculiarities of the course in the eye cavity, where they are located, as well as with the place of attachment to the eyeball wall. Thanks to these muscles, the eyes can perform numerous movements, both unidirectional and multidirectional. Unidirectional turns are up, down, left and others, and multidirectional - bringing the gaze to one point.

When measuring the trajectory of eye movement, there are always noises that are random in magnitude and direction and are superimposed on real gaze displacements. For the registering equipment used, the resolution is 0.01° , and the working accuracy is $0.25^\circ - 0.5^\circ$ [10], which in the image plane on the monitor is 0.14, 3.5 and 7.0 mm, respectively (distance to the image is equal 800 mm).

To study the angular distribution of gaze displacements in fixations and saccades, a landscape image with a pronounced horizon line and with a set of vertical elements was used. To reduce the influence of the dominant directions (vertical and horizontal), the image was rotated 315 degrees (**Fig. 11**).



Fig. 11. Test images to study the angular distribution of gaze displacements in fixations and saccades.

The division of the trajectory of eye movement into fixed states and saccades was carried out according to known methods [4].

To study statistical characteristics, it is necessary to first perform the following operation: find the coordinates of the "center of gravity" (mean values) for each sampling (or simply the center of the fixation) and subtract the corresponding mean values from each of its coordinates. Having performed such a transfer operation for each fixation and having built a cumulative tracking system, one can get a complete picture of the gaze movement in all fixations when viewing this image. By performing this transfer operation for each fixation and building an aggregate tracking system, one can get a complete picture of the gaze movement in all fixations when viewing that image. Having processed the total set of trackings, we get statistical characteristics, the distribution of points in fixations, for example, along the X and Y axes, corresponding to the variance of distributions, etc. The advantage of this approach is that it is possible to compare the fixations obtained when viewing different patterns by the same testee, and by combining them, one can easily collect the necessary statistics.

Fig. 12a shows an aggregate of the set of points for all fixations in one image, plotted relative to a single center of gravity. The trackings registered by the measuring system in fixed states (fixations), corresponding to the gaze displacements in these areas, at least visually look very similar to a random process. In order to compare the results, **Fig. 12b** shows samplings for a true normal process, generated by a random number generator with dispersions in X and Y the same as for the experimentally recorded process.

When observing the trackings of eye movement built for an aggregate of fixations, it is seen that the gaze moves within a limited

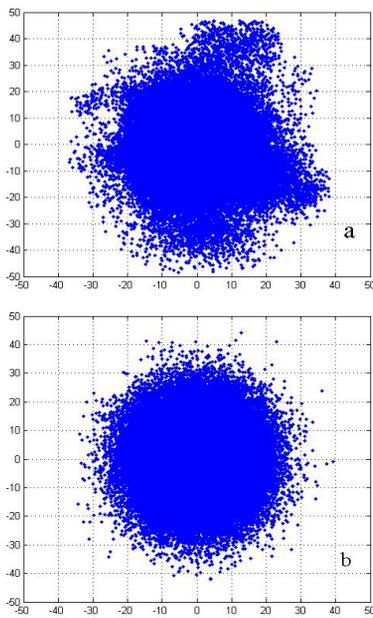


Fig. 12. *a* - the aggregate of the set of points in all image fixations, obtained in the experiment, *b* - modeling of the fixation by random number generator samples.

area in a chaotic manner (Fig. 12a). It can be seen from the figure that individual points fall out of the specified area, but, due to the large statistics, this practically does not affect the final result.

A typical example of such an angular distribution for the image in Fig. 11 is shown in Fig. 13. It can be seen that the angular distribution demonstrates clear asymmetry for all displacements of N_s (green line), as well

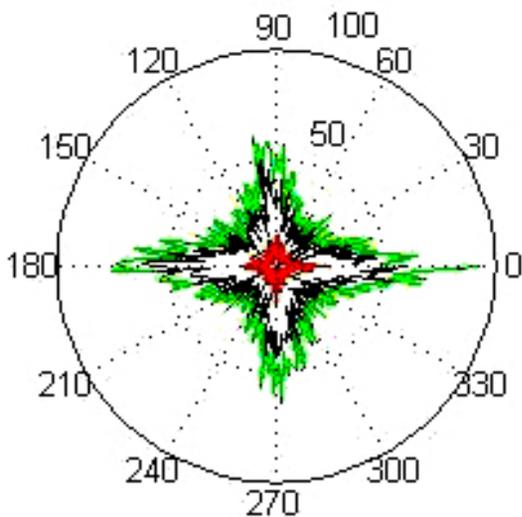


Fig. 13. *Angular distribution of displacements in all fixations for the image in Fig. 11.*

as for smaller (red line) and larger (black line) values.

By analyzing the angular distribution for different values of gaze displacements, it is possible to determine the threshold displacement value when the distribution becomes asymmetry. It should be noted that in this case it is necessary yet to exclude "transitional" displacements from fixations to saccades and vice versa, although they are unlikely to have any effect on the summar angular distributions, due to their small number and the absence of any selected direction in the fixation. The resulting distributions are shown in Fig. 14 at different values of the gaze displacement (LV). The distribution statistics include 267,290 displacements.

Fig. 14 clearly demonstrates that with an increase in the cutoff level (displacements whose length is less than the LV threshold are taken into account), the asymmetry in the angular distribution increases, more and more the horizontal and vertical directions of the gaze displacement begin to prevail, and ultimately the angular distribution tends to the shape of a cross (Fig. 13).

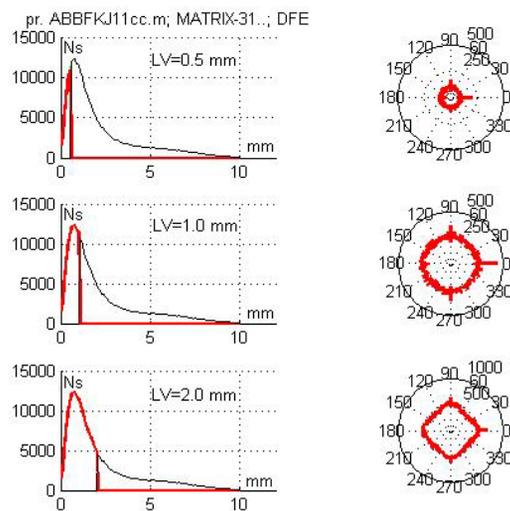


Fig. 14. *Distributions of displacements along the length (left), threshold (0.5, 1.0 and 2.0 mm, vertical line on the graphs on the left), less which the displacements are selected and angular distributions are plotted for them (right).*

Thus, up to gaze displacements $LV = 1$ mm, we are dealing with noises of the registering measurement system, the maximum of which is approximately 0.8 mm, which have a normal distribution along the length, and are uniformly distributed over the angle, which and observed in Fig. 14. With the growth of displacements, noises in angular statistics plays an ever smaller role, and the role of real of gaze displacements is increasing, as indicated by the angular distribution by changing its shape, deviating more and more from the correct circumference.

7. CONCLUSION

The paper explores some features of the gaze movement in fixations and saccades during visual perception of images and reading texts. It is shown that in the fixations region there are so-called multiple displacements, the frequency of which exceed two or more times than that for model artificial random fixations.

It has been shown that the left and right eye tracking may differ. This is observed both on the trackings itself and on the angular distributions of displacements.

It is shown that the angular distributions of gaze displacements are not uniformly. Vertical and horizontal directions evidently stand out on they. This is characteristic not only for strictly deterministic processes (reading), but remains true and when considering neutral images, including those rotated at different angles.

It was determined the noise error of the eye-tracking recording system when registering the gaze displacements. It is shown that down to gaze displacements of the order of 1 mm, the noises of the registering measurement system prevails, which have a normal distribution along the length, and are uniformly distributed over the angle.

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