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TEMPORAL DYNAMICS OF FIXATION DURATION, SACCADE AMPLITUDE, AND VIEWING TRAJECTORY

LUBOV N. PODLADCHIKOVA
A.B. Kogan Research Institute for Neurocybernetics,
Southern Federal University, 194/1, Stachki ave.,
Rostov-on-Don, 344090, Russia
lnp@nisms.krinc.ru
http://nisms.krinc.ru/lnp_en.htm

DMITRY G. SHAPOSHNIKOV
A.B. Kogan Research Institute for Neurocybernetics,
Southern Federal University, 194/1, Stachki ave.,
Rostov-on-Don, 344090, Russia
shaposhnikov@nisms.krinc.ru

TATIANA I. KOLTUNOVA
Psychology Department,
Southern Federal University, 13A, Nagibina st.,
Rostov-on-Don, 344038, Russia
t.koltunova@gmail.com

ANNA V. DYACHENKO
Psychology Department,
Southern Federal University, 13A, Nagibina st.,
Rostov-on-Don, 344038, Russia
nisms@krinc.ru

VALENTINA I. GUSAKOVA
A.B. Kogan Research Institute for Neurocybernetics,
Southern Federal University, 194/1, Stachki ave.,
Rostov-on-Don, 344090, Russia
gusakova@nisms.krinc.ru

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The prospective goal of our study is a quantitative estimation of the contribution of various factors and mechanisms during image viewing. In this paper, experimental data about temporal dynamics of eye movements parameters and viewing trajectory were considered. Three images were presented to each of subjects (n=12) under two experimental conditions: “free viewing of initial images” and “search for modified regions in previously presented images”. Averaged fixation duration and saccade amplitude as well as a type of viewing trajectory were determined in each consequent period of trials having 30 fixation points. Viewing trajectories were classified into three types: (1) scanning, (2) grouped, and (3) mixed. In spite of individual variations (subject and image), several common peculiarities of temporal dynamics of image viewing were revealed. Specifically: (i) fixation duration in the first and last trial periods were less than during the second one; (ii) saccade amplitude had the opposite dynamics; (iii) the scanning trajectories dominated in the first and last periods as compared with the second one; (iv) the mixed and grouped trajectories are more pronounced in the second period; (v) independent of their temporal consequence, the periods with maximal fixation duration differed from those with minimal duration by saccade amplitude and dominating viewing trajectories.

Keywords: Temporal dynamics of viewing trajectory; fixation duration; saccade amplitude.

1. Introduction

It is well-known that the choice of areas of interest for gaze fixation during image viewing depends on several factors and is determined by both perceptual and cognitive mechanisms [1, 2, 5, 6, 7, 8, 9, 11, 12, 18, 26, 29, 33, 36, 37, 39, 40, 41]. As compared with the cognitive mechanisms, contribution of perceptual mechanisms into this process can be more exactly evaluated by image features and eye movement parameters. Exact quantitative estimations of various factors received in standard experimental conditions are necessary to accumulate the known data for correct understanding of image viewing mechanisms. However experimental conditions in different laboratories (trial task, stimulus/image type, eye tracker system, etc.) vary widely. Such variations may be one of the main reason for inconsistency of the results obtained [12, 30]. Currently, the well-accepted consistent facts are: (i) at preattentive level, image regions with maximal brightness and contrast as well as big objects are preferable for gaze shift from a current fixation point [40]; (ii) to activate visual attention, image regions must be located on some distance (no less than 2-10° in the visual field) from the current fixation point [9, 11, 39, 40]; (iii) "centre of mass" of areas of interest and their enveloping contour may be considered as the important image properties for gaze positioning [1]; (iv) viewing scanpath topology is a specific attribute of the given image during memorizing, recognition, and mental imaginary [14, 17, 23]; (v) viewing trajectory details for the same image depend on the subject motivation (viewing instruction) before a psychophysical test [40]; (vi) fixation duration and saccade amplitude vary widely at initial experiment stages and are relatively stable during later stages [19, 35, 36].

Taking into account a poor formalization and some contradictions of the known experimental findings, mathematical modeling is considered to be an important tool to study the image viewing mechanisms [8, 9, 14, 16, 17, 23, 38, 41]. In the most of modeling research, the contribution of some gaze shift factors is analyzed in detail while other factors are ignored. In particular, some authors consider mainly primary image features or saliency maps [5, 34], the attention mechanisms [18, 27, 28, 41], or relationship between the sensory and motor memories [17, 23]. In the review paper [38], it is noted that the development of realistic models to analyze the contribution of various factors and mechanisms of different levels during image viewing remains an actual task. The results of computer simulations with such models may be useful to generate the suggestions about possible mechanisms of image viewing which can be verified experimentally.

The temporal dynamics of eye movements trajectory (scanpath) during viewing of complex images is one of the less studied problem [12]. Taking into account the facts listed above, detailed data about temporal dynamics of viewing trajectory, eye movements parameters (fixation duration, saccade amplitude, etc.), and areas of interest may give an important criteria for objective estimation of the visual task to be solved during current viewing stage.

Our approach to formalize the related experimental data [21] includes the following steps: (i) the choice of the published results with detailed protocols and the primary data of psychophysical experiments (for example, such as in [40]) for their secondary quantitative analysis; (ii) the development of a computer model that can imitate the results of a particular experiment (similarly to the authentic modeling approach [4]); (iii) the space-variant analysis of local visual features around each fixation point (similarly to [24]); (iv) some modifications of initial images and the conducting of verification psychophysical experiments with presentation of the images which were used in the published studies; (v) the determination of multi parametric gaze attraction function. Overall goals of our study are as follows: a quantitative estimation of the contribution for various factors received in the standard experimental conditions, the search for objective criteria to identify the transition moments from ambient (spatial) attention to focal one (and vice versa), and the development of a realistic model of image viewing mechanism's hierarchy.

The current main results of the implementation of this model-based approach based on tight mutual connections between psychophysical experiments and mathematic modeling [7, 21, 22, 27, 28] consist in the following: the algorithms for detection of an areas of interest based on the psychophysical results with high-accuracy tracking of eye movements; identification of three basic types of eye movements trajectories (i.e., the "viewing", "object-consequent", and "object-returned" ones); several versions of the gaze attraction function for formation of viewing trajectories similar to the experimental ones; preliminary data about task-related and temporal dynamics of eye movements parameters during image viewing.

In this paper, more detailed data about temporal dynamics of viewing trajectory, fixation duration, and saccade amplitude at consequent stages of complex images free viewing and search for their modified regions are presented.

2. Materials and Methods

The SMI iView X Hi-Speed 1250 eye tracker was used to record the eye movements. According to the quantitative analysis [21] of some published data, three pictures used in Yarbus' experiments [40] were chosen as basic stimuli, namely the paintings: "Ne zhdali", I.E. Repin (Im1), "V lesu grafini Mordvinovoy", I.I. Shishkin (Im2), and "Berezovaja rosha", I.I. Levitan (Im3). 12 volunteers participated in the experiments. For each subject, the images Im1-Im3 were presented for viewing with the one of two instructions namely: “viewing of initial images” and “search for the modified (blurred) regions in the previously presented images”. As can be seen in Fig. 1, the chosen images have different number of the semantically important objects. The images were displayed on computer screen located at the distance of 80 cm from a subject. The size of the modified image regions was equal to 2°; for each subject and image, they were located in the image regions distinguished by the density of gaze fixations in the experiments with free viewing of each image. Each trial was finished when a subject stated that “the image is viewed for its description” or “all modified image regions are found”); after the trial, a detailed subject voice report was recorded. While processing of primary experimental data by BeGaze algorithms included into SMI iView X Hi-Speed 1250 system peak velocity threshold for saccade detection was equal to 100°/s. Trial periods with possible error events such as pronounced temporal trend, blinks, saccade with amplitude more than 30°, very short serial gaze fixations with duration less than 40 ms, and the fixations located outside stimulus screen have been rejected from further analysis.

Fig. 1. Test images (Im1-Im3). The image size in pixels indicates under each pictures.

To group the gaze fixation points for identification of the areas of interest (as image regions with local groups of the gaze fixations in the foveal visual field) and classify viewing trajectory, the nearest neighbor method [20] and a set of determinative rules [21] have been used. During analysis of the primary image features around each fixation point convolution matrices inside input window regions have differed dimensions. The initial data were used for image representation at the first resolution level (the “foveal” region of the input window), to present the image at the second (the “parafoveal” regions) and third (the “perifoveal” regions) resolution levels the initial image was transformed by the recursive Gaussian-like convolution [3]. Edge contrast and its orientation at each resolution level were determined by a difference between two Gaussian convolutions with spatially shifted centers [13]. The discrete angle step of 22.5° was considered as a unit in all angular measurements.

3. Results and Discussion

3.1. *Comparison of eye movements parameters during free viewing and search for modified regions in the image*

The results of free image viewing and search for modified regions in this image were compared by location of the areas of interest, fixation duration, and viewing scanpath. The number of the areas of interest detected during the whole trial was less for free viewing as compared with search for modified image regions (in average, 5 and 8 areas, correspondingly) and they were widely spread throughout the image during the last trial (Fig. 2). The areas of interest had higher density of gaze fixations during free viewing as compared with search.

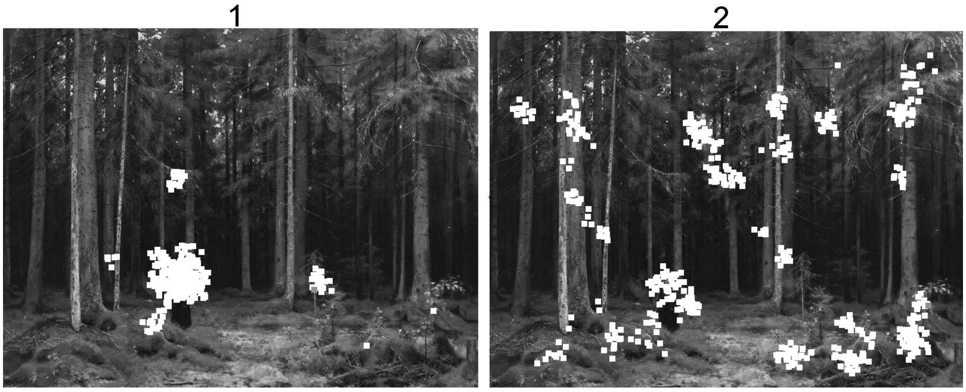


Fig. 2. Spatial distribution of gaze fixation points during the free viewing of Im2 (1) and search for modified regions in this image (2). The cumulative data for all subjects with density thresholding of gaze fixation points have been used in the both cases.

It was shown that, during the free viewing, a spatial location of the areas of interest was depended on image type: in Im1 and Im2, they were located in vicinity of the main objects in the images and arranged along horizon line in Im3 (see Fig. 4 and 6 in Section 3.3.). Fixation duration for the areas of interest located inside the objects on Im1 and Im2 which were noted in the subject reports was more than for the areas located in the ignored image regions (in average, 478.94±14.22 ms and 113.65±6.19 ms, correspondingly). This fact allows to explain the known findings [32] about the differences between the areas of interest detected by fixation density and fixation duration. In particular, in spite of similar fixation density for different areas of interest only a part of them with a greater semantic importance for a subject may be characterized by higher fixation duration. This problem demands a detailed investigation in future.

During each trial (n=72), fixation durations and saccade amplitudes were varied. In the most trials (about 80%), the coefficient of variation for fixation duration was more than that for saccade amplitude (in average, 94% and 75%, correspondingly).

Similar differences for fixation duration are revealed between trials with free viewing and search for the modified image regions (104% and 85%, correspondingly). Fig. 3 demonstrates an example of such dynamics for the consequent trial periods. These facts indicate that eye movements parameters during a visual search are more stable than during free viewing.

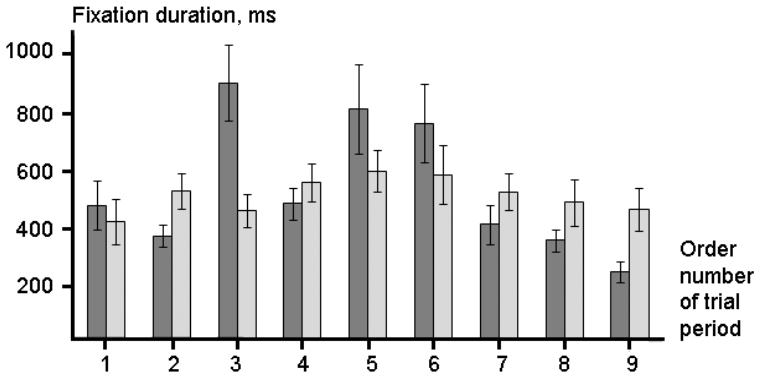


Fig. 3. Examples of temporal dynamics for fixation duration during free viewing of Im1 (■) and search for its modified regions (□). Averaged fixation duration and standard error (vertical lines) for consequent trial periods for the subject M. are shown.

The revealed differences between "free viewing" and "search" experiments indicate that the solution of these visual tasks has specific strategies in the visual perception. Evidently, the mechanisms of the spatial attention dominate during the search experiments while the mechanisms of the focal attention are more pronounced during free viewing. Such differences may be a possible reason for contradictions between the known data about the contribution of local visual features to gaze shift (compare [7] and [39]).

3.2. *Temporal dynamics of eye movements parameters*

The results of each trial were divided into the consequent temporal periods including 30 gaze fixations. The averaged fixation duration and saccade amplitude as well as trajectory type were determined for each period. The trials (n=34) with 4 and more such periods (in average, 8) were chosen for the detailed analysis. An expressed dynamics of fixation duration and saccade amplitude in the consequent trial periods was revealed in the most of trials for both free viewing and a search for the modified image fragments (n=25) with using three test images.

In spite of individual variations (for the subjects, images, and tasks), two common peculiarities of the temporal dynamics for fixation duration and saccade amplitude were revealed. The first peculiarity is illustrated by data presented in Table 1. As can be seen, fixation duration is increased in the second temporal trial period as compared with the first one and decreased in the last trial period when a subject makes the decision to finish a experiment. Saccade amplitude has opposite temporal dynamics. All indicated differences are confident (p=0.001, the Student's t-test [25]). These results are in agreement with the well-known data about temporal dynamics of fixation duration and saccade amplitude during several first gaze fixations [19, 35, 36]. The fact about changing of eye movements parameters during the last trial period does not agree with the known data about their relative stability during later trial stages [19, 35, 36]. This inconsistence can mainly be determined by the differences between experimental methods (in our case, a decision to finish experiment was made by a subject) and data analysis (the averaged values for consequent trial periods in our case versus consequent single events in the most studies). The presented results about temporal dynamics of the eye movements parameters indicate that the preattentive mechanisms may dominate at the first and last stages of image viewing.

Table 1. Temporal dynamics of fixation duration and saccade amplitude.

Eye movements parameters	The first trial period, n=25	The second trial period, n=25	The last trial period, n=25
Fixation duration, ms	468.67 ± 4.23	570.50 ± 5.31	403.82 ± 2.96
Saccade amplitude, degree	4.00 ± 0.02	3.42 ± 0.02	4.39 ± 0.05

The second common peculiarity of a dynamics of the eye movements parameters is illustrated by the data presented in Table 2. Three types of trial periods were determined during each trial according to the difference of the mean values of fixation duration for the given trial period and the trial as a whole. The differences were estimated at level of 2σ [25]. Independent of the order number of trial period in the temporal sequence, three groups of the periods were found in each trial: (1) the mean fixation duration in a period is less than that for the whole trial; (2) the mean fixation duration in a period does not differ from the mean value for the whole trial; (3) the mean fixation duration in a period is more than that for the whole trial. For the data presented in Fig. 3, for example, the period "9" during free viewing and the period "1" during search were included into the first group; the periods "3", "5", "6" during the free viewing and the periods "5", "6" during search were included into the third group. There is a trend for saccade amplitude decrease from the period group with minimal fixation duration to the group with maximal fixation duration (see Table 2). Saccade amplitude differences between the first and third groups are confident (p=0.001, the Student's t-test [25]).

To some extent, these results are consistent with the well-known data about

Table 2. Saccade amplitude for the trial periods with different fixation duration

Eye movements parameters	Fixation duration less the mean value, n=53	The mean fixation duration, n=150	Fixation duration more the mean value, n=57
Fixation duration, ms	397.70 ± 13.07	553.58 ± 13.32	777.44 ± 26.89
Saccade amplitude, degree	3.87 ± 0.11	3.64 ± 0.08	3.23 ± 0.09

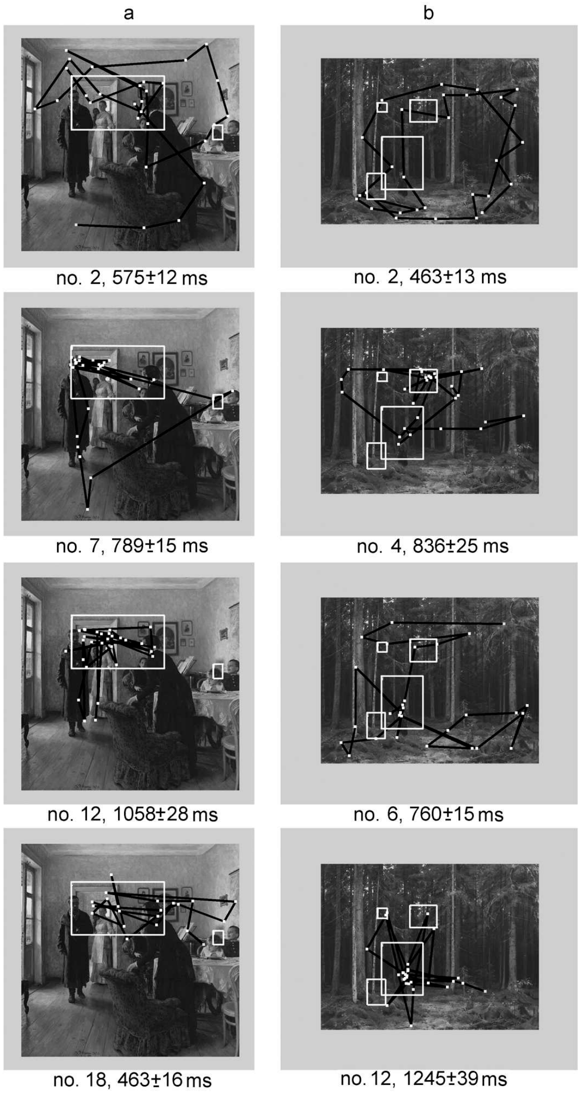
negative correlation between the duration of the preceding eye fixation and the amplitude of the following saccade based on comparison of the paired events [36, 37]. Evidently both facts may be integrated to develop the mathematical algorithms for exact detection of the transition moments from the focal attention to the spatial attention (and vise versa) during the consequent viewing.

3.3. *Temporal dynamics of image viewing trajectories*

It was revealed that viewing trajectories were changed during each trial (Fig. 4). The algorithm developed earlier [21] to classify the viewing scanpaths was modified for more detailed estimation of trajectory temporal dynamics. In each trial period, the relation of the grouped (located inside local image regions) and non-grouped fixation points was determined. On the base of this relation, the trajectories were divided into three types: the grouped (more 20 grouped fixations), scanning (more 20 non grouped fixations), and mixed ones.

Similar to eye movements parameters described above, two common peculiarities of viewing trajectory temporal dynamics were revealed. The first common peculiarity is illustrated in Fig. 5, I. Here, the relation between three types of trajectories for the same trial period types as in Table 1 is presented. There is some tendency for the domination of the scanning trajectories in the first and the last trial periods and the mixed (and grouped) scanpaths in the second trial period (Fig. 5, I). Such trajectory dynamics corresponds to changing of the fixation duration and saccade amplitude in these trial periods (see Table 1).

The second common peculiarity of viewing trajectory dynamics is illustrated in Fig. 5, II. Here, the relation between three types of the trajectories for the same period types as in Table 2 is presented. As can be seen in Fig. 5, II, there is a trend to decrease the scanning trajectories number from the periods with the minimal fixation duration to the periods with the maximal fixation duration and inverse dynamics for the grouped trajectories. The trial periods “1” and “3” in the Fig. 5, II are confidently different from each other on number of the scanning and the grouped trajectories (p=0.001, the Student’s t-test). The presented results about viewing trajectory dynamics and its correlation with eye movements parameters (i.e. fixation duration and saccade amplitude) give some quantitative details to the phenomenon



no. 2, 575±12 ms
no. 2, 463±13 ms
no. 7, 789±15 ms
no. 4, 836±25 ms
no. 12, 1058±28 ms
no. 6, 760±15 ms
no. 18, 463±16 ms
no. 12, 1245±39 ms

Fig. 4. Examples of temporal dynamics of eye movements trajectories during the free viewing of Im1 (a) and Im2 (b). The data for selected consequent trial periods of the subject I.1. are shown. In each image in Figs. 4 and 6, the areas of interest detected during whole trial are marked by the white rectangles; the order number of trial period and the mean fixation duration are indicated under each picture.

of scanpath changing for the same subject originally described in Yarbus' work at the qualitative level [40]. Besides, they indicate that widely accepted global strategy of image viewing (for example [19]) may have local transitions to opposite strategy.

It has been revealed that the trajectory type and its temporal dynamics depend on pecularities of the subject's visual perception (Fig. 6). In particular, the grouped scanpaths dominated during all stages of the free viewing of the three images for the subject I.1. (see Fig. 4 and 6a); but the scanning trajectories are more expressed

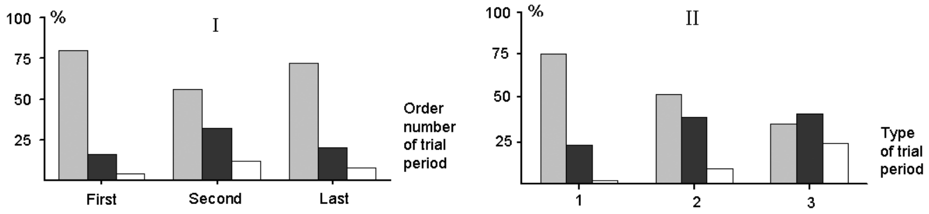


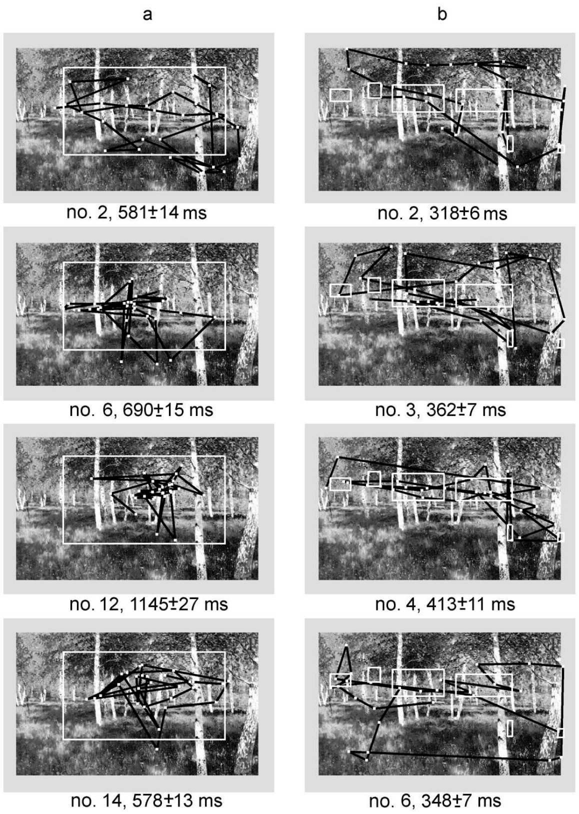
Fig. 5. Temporal dynamics of trajectory types during a trial. (▨), (☐), (■) - the scanning, grouped, and mixed trajectories, correspondingly. (I): Relation of trajectory types in the first, second, and last trial periods; (II): Relation of trajectory types for trial periods with different fixation duration. "1", "2", "3" - the trial periods with the minimal, middle, and maximal fixation duration, correspondingly.

the subject IV.1. (see Fig.6b). The relation between the grouped and scanning trajectories for all trial periods during the free viewing of these subjects are as follows: 50% and 18% for the subject I.1. (the number of trial periods is equal to 50); 16% and 58% for the subject IV.1. (the number of trial periods is equal to 19); these differences are confident (p=0.01, the Student's t-test). The obtained data indicate an opportunity of a quantitative estimation of dominating visual attention mechanism (the focal or ambient one) for each subject by means of detailed analysis of spatial distribution of gaze fixation points during the consequent viewing stages.

3.4. *Comparison of primary local features density and gaze fixation duration*

At present, the known data about relation between local primary image features and eye movements parameters during the free viewing and search are very contradictory [5, 10, 24, 33, 34, 39]. In particular, some authors revealed that image regions with differing gaze fixation density had no differences from each other for the most primary features and their combinations [10, 21]; in other works [5, 16, 39], an opportunity to predict the viewing scanpaths by image saliency maps is stated.

To elucidate some aspects of this problem the following analysis of experimental data was performed (Fig. 7). At the first stage, all experimental data obtained during the free viewing of Im2 were accumulated. Then after density thresholding, the areas of interest were detected by fixation points grouping (numbered as (1-4) in Fig. 7, I). At the next stage, four screen regions (outside the image) with episodic gaze fixations (indicated as (a-d) in Fig. 7, I) were chosen. At the last stage, the density of local oriented edges and the mean fixation duration inside each chosen region were calculated by input window imitating the human foveal visual field (2°). Particular position of input window is presented at right side in Fig. 7,I. It has been revealed that fixation duration varies independently of primary feature density inside different areas of interest (Fig. 7, II). Contrary to this, for screen regions with episodic gaze



no. 2, 581±14 ms
no. 2, 318±6 ms
no. 6, 690±15 ms
no. 3, 362±7 ms
no. 12, 1145±27 ms
no. 4, 413±11 ms
no. 14, 578±13 ms
no. 6, 348±7 ms

Fig. 6. Individual temporal dynamics of eye movements trajectory during free viewing of Im3. The data for selected consequent trial periods of the subjects I.1. (a) and IV.1. (b) are shown.

fixations their duration (see Fig. 7, III) increases in parallel with a growth of feature density. These facts together with those described in Section 3.1. allow to suppose that: (1) the semantic importance of the areas of interest is main "determinant" of fixation duration; (2) a quantitative estimations of the semantic importance for different image regions are possible by joint analysis of fixation density and duration.

4. Conclusion

Taken together, the results obtained indicate that there is the parallel dynamics of the trajectory topology, fixation duration, and saccade amplitude during different stages of the viewing/search for modified regions of complex images. In particular, it was shown that: (i) the fixation duration in the first and last trial periods was less than during the second one; (ii) the saccade amplitude had the opposite dynamics; (iii) the scanning trajectories dominated in the first and last periods as compared with the second one; (iv) the mixed and grouped trajectories were more pronounced in the second period; (v) independent of their temporal consequence, the periods with maximal fixation duration differed from those with minimal duration by sac-

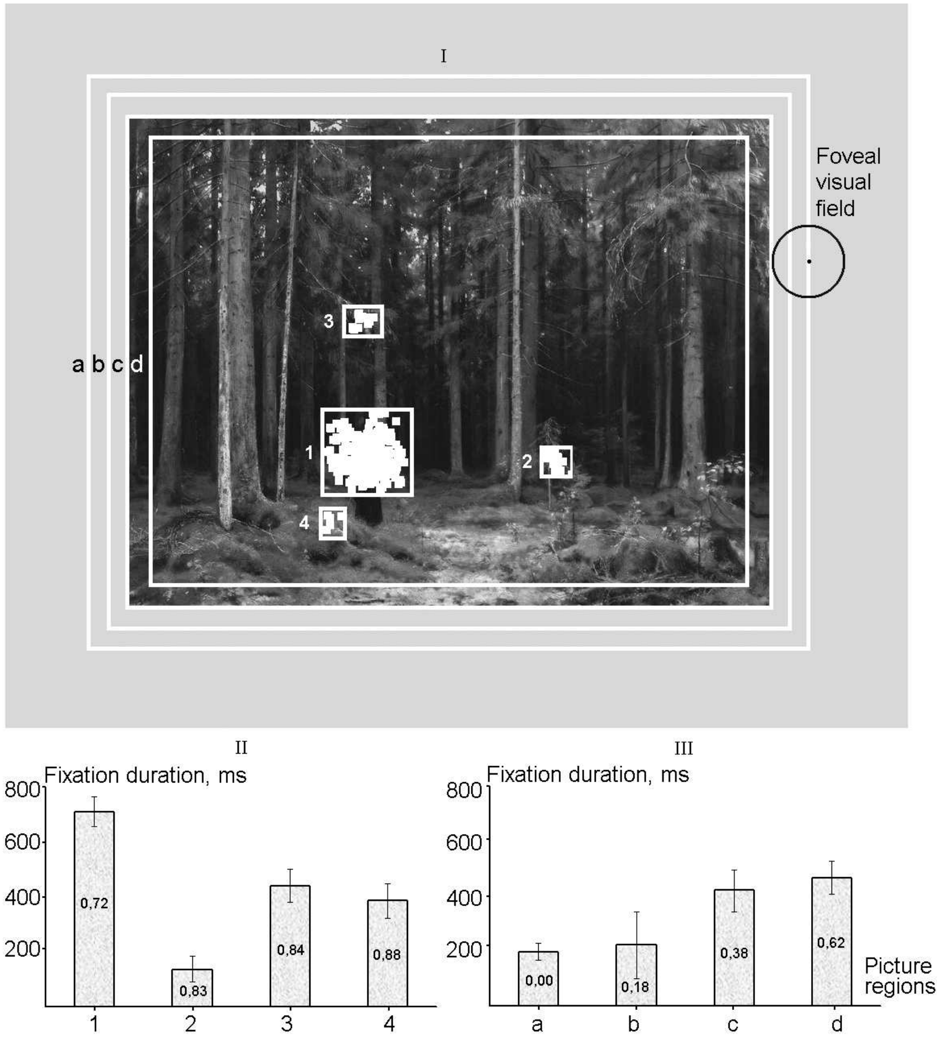


Fig. 7. Comparison fixation duration and primary features density inside different image regions. I: scheme for comparison of primary features density and fixation duration; (1-4) - detected areas of interest, (a-d) - screen areas with episodic gaze fixations. II and III: the mean fixation durations and standard error (vertical lines) in (1-4) and (a-d), feature densities are indicated inside each bar.

cade amplitude and dominating viewing trajectories. The revealed similarity of the temporal dynamics for eye movements parameters and the trajectory topology are important to develop an algorithms for multi parametric gaze attraction function in addition to ones developed earlier, namely: the areas of interest-based and the feature-based attraction functions [27, 28].

Further detailed investigation of the revealed phenomena by an approach [21] based on tight interaction between the experiment and modeling will give an opportunity for quantitative estimations for the following: (i) a contribution of various "determinants" [1] during dynamical process of complex image viewing by means of special algorithms of the experimental data analysis and the realistic attraction function to imitate a particular experiment; (ii) the transition moments from focal attention to spatial attention (and vise versa) during the consequent viewing; (iii) a criterium for objective evaluation of the visual task to be solved during a current viewing stage; (iv) a criterium for image objects (the areas of interest) classification according to their semantic importance by joint analysis of fixation density and duration; (v) a criterium to determinate the dominating visual attention mechanisms (focal or spatial one) for each subject.

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