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Eye Tracking and Interhemispheric Interaction in the Distribution of Spatial Attention

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Abstract—The patterns of visual attention allocation were investigated in healthy subjects (n = 43) and patients with focal brain lesions (n = 17) using the original method developed for eye tracking in patients while memorizing a series of stimulatory image triplets. Two processes were estimated: delayed reproduction and recognition of stimuli in a series of consecutive visually similar distractors. In healthy subjects both processes correlated to a great extent ($r = 0.6$; $p = 0.00001$). The most significant disorders of voluntary verbal reproduction were observed when the left hemisphere of the brain was affected. The overall effectiveness of recognition in the case of brain damage decreased without significant dependence on the lateralization of the focus. Some correlation was observed between realized and remembered information and the patterns of visual fixations (concentrated on the semantic parts of the image or chaotically distributed in the space of stimulus exposure). Ineffective patterns of visual fixation in patients were more often observed in the area contralateral to the lesion. These contralateral stimuli were reproduced and recognized less efficiently in comparison with the central and ipsilateral images. Complete ignoring of the contralateral image in the triplet was observed both in the absence of visual fixation and in combination with the diffuse pattern.

Keywords: eye tracking, attention, memory, interhemispheric interaction, fixed left-sided agnosia (unilateral spatial neglect)

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Attention allocation in the visual field is not homogeneous. It depends on many factors, primarily, on the semantic characteristics of the surrounding space, human activity, his or her goals, interests, and previous experience [1]. Another factor influencing attention allocation is the current features of interhemispheric interaction of an individual. Experiments with a homogeneous stimulus field allow this factor to be detected. For example, in one of the studies, the subjects were presented stimuli as multiple dots resembling a picture of the starry sky against the dark monitor screen. Two mutually perpendicular lines divided the screen into four equal parts (Fig. 1). The number of dots was not amenable to calculation, but there were 15% more dots in one of the parts of the screen than in the others. The subject was required to show in which part of the screen he thought there were more dots. The predominant field appeared in the pseudorandom order in some part of the screen in the course of 40 exposures. At no stage of task performance did the subjects receive feedback as to whether their choices were right or wrong. Task performance by healthy subjects did not show a statistically significant predominance in the choice of one of four segments. Note that in the group of patients with local brain lesions (53), overtly impaired attention was recorded in the part of the visual field contralateral to the lesion. These areas were chosen rarer, and the accuracy of the answers was significantly lower ($p < 0.05$) than in [2].

The problem of attention allocation in the visual field in the clinical picture of focal brain lesions is coupled with the problem of visual agnosia. The most obvious link is traced to fixed left-sided agnosia in space, referred to as *unilateral spatial neglect* [3, 4]. Various modifications of the theory of occult shifts in attention to the side contralateral to a functionally more active hemisphere are most often used as an explanatory principle [5]. Note that the greatest difficulties arise when an attempt to explain the absence of symmetrical phenomena of neglect of the right side of space in left hemispheric lesions is made. Novel technologies used to solve this task expand the spectrum of the hypotheses discussed. For example, one of the large studies conducted in recent years using resting state functional magnetic resonance imaging (fMRI) at rest showed that during actualization of the default mode network including, apart from other structures, hippocampal regions, the right hippocampus links demonstrated bilateral hemispheric representation, and the left hemispheric links integrated information flows only collaterally. Such functional asymmetry partly explains the clinical phenomenology of the left-

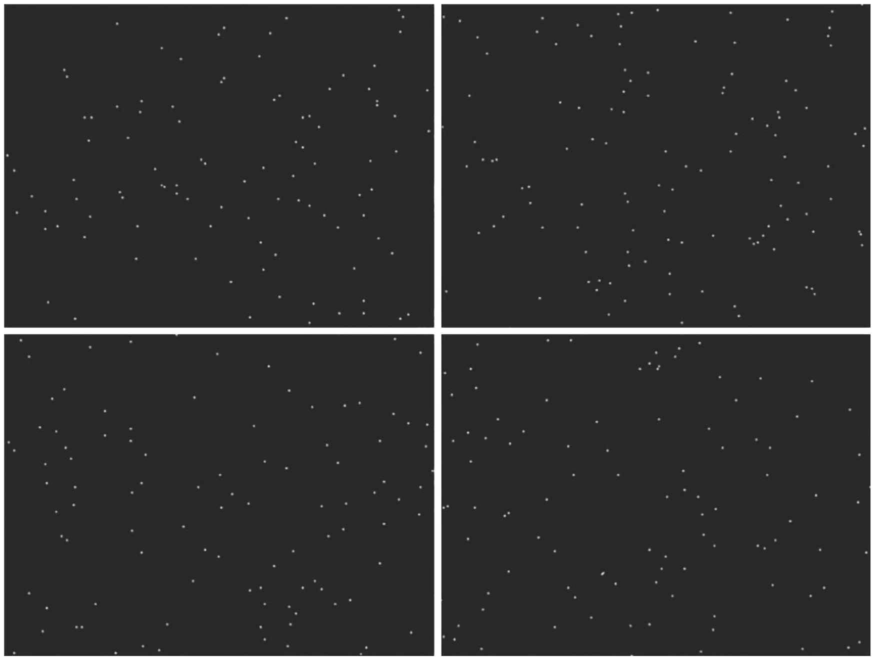

Fig. 1. Example of a homogeneous stimulus field when studying the role of interhemispheric interaction in attention allocation [2].

sided neglect but does not completely solve all the relevant problems [6].

Eye movement recording (oculography) has long been used in studying the mechanisms of attention allocation. The studies by Yarbus, who was one of the first to demonstrate a strong correlation between the eye movement trajectory in viewing complex subject images and the task facing the subject have gained worldwide recognition [7]. The modern systems of contact-free recording of gaze direction are most often based on infrared lighting and a video camera tracking the position of the eyeballs for computer-aided signal processing. The gaze coordinates, i.e., the points of intersection of the eyeball axes with the planes of the object observed or the screen where a visual stimulus is presented are determined (this technology is referred to as "eye tracking") [8]. Gaze direction is regarded as an indicator of attention and allows the solution of a broad spectrum of the tasks connected with its spatial allocation. For example, in clinical studies, this technology is used for differential diagnosis of coma, the vegetative status, and the minimally conscious states [9, 10]; the features of attention are studied in patients with aphasia [11]; oculomotor defects are qualified [12].

The problem of attention in clinical and experimental studies is closely linked to the problem of memory. What information remains in the subject's memory in different strategies of perception and attention? The implementation of two types of activity in parallel has been shown to influence the distribution of visual fixations [13]; emotion-induced stimuli attract more attention and are better retained in memory [14]; the comparison between the eye movement trajectories on the first and repeated stimulus presentation may serve as an indicator of the completeness of information about this stimulus stored in the subject [15].

The methodological technique of this study was aimed at assessing interhemispheric interaction in the course of spatial attention allocation recorded by eye tracking and the additional objectification of the studied processes by reproducing and recognizing the stimuli stored in the subject's memory.

METHODS

Forty-three healthy subjects (29 women) whose ages varied between 19 and 81 years (average age, 46 ± 24 years) participated in the study. The clinical group included 17 patients (all right-handed) with focal lesions (brain tumors) of the temporal and temporal-occipital divisions of the left (7 patients) or right (10 patients) cerebral hemispheres. The topical verification of the focus of lesion was performed based on the contrast medium examination data and the protocols of neurosurgical treatment.

For all participants in the study, Russian was the native language. According to the preliminary testing data, none of the subjects had any difficulties in recognizing and naming the pictures similar to the composition of the stimulus material in the Methods of this study.

The eye movements of the subjects were recorded using an Eye Tribe eye tracker (sampling frequency, 30 Hz; accuracy, 0.5–1). Image presentation was carried out using the Ogama software (Open Gaze and Mouse Analyzer). The eye movement trajectories were processed using the Matlab software package. When being analyzed, the stimulus triplets were divided into three similar rectangular regions, each containing the left, middle, or right picture of the triplet. The number of visual fixations was calculated in each of the regions. The screen gaze coordinates recorded by the eye tracker were superimposed on the images in the pictures at a resolution of 1920 × 1080.

The procedure of performing the method for eye movement recording (**E**ye Tracking), assessing spatial attention allocation (**A**ttention) and **M**emory characteristics (**M**emory), hereinafter the EAM Method, consisted in the following. The subject was presented stimuli on the display and instructed to look at them carefully and remember. The stimuli were three colored pictures arranged in a row (a triplet of pictures). The exposure time was 10 s for each triplet. Before triplet presentation, also for 10 s, a gray screen was exposed (before the experiment, the subject was instructed to simply relax and not to do anything during exposure of the gray screen). The experimental set contained five triplets (15 pictures) and six exposures of the gray screen framing the stimulus material in time. The overall presentation time was 110 s. The presentation was accompanied by recording the subject's eye movements.

The subjects were not given any instructions about what part of the screen their gaze should be fixed on during the pauses and before exposure of the stimulus material. The strategies of visual attention allocation chosen by them were regulated only by their own spontaneous activity. Recoding visual fixations allowed us to analyze both the overall gaze trajectory over each of the 10-s exposures and distribution of fixations in time, e.g., to single out the first five and the last five fixations for each triplet.

Ten minutes after stimulus presentation (before the performance of the EAM method and during the interference intervals, the subject performed the tasks of neuropsychological investigation according to the method of Luriya and a battery of psychophysiological tests), the second stage of the EAM method occurred. The second stage consisted in free reproduction of the stimuli stored in memory. The subject had to recall and name the pictures he had seen on the screen in any order. The subject's answer was entered in the protocol.

Fifteen minutes later, the procedure of stimulus material recognition was performed. Single pictures, among which there were both absolutely identical to the initial sample and slightly differing from it in small details, color, and the arrangement in space, emerged on the monitor screen in the pseudorandom order. Absolutely new pictures, in no way connected with the initial sample were among the distractors. Accordingly, when each picture emerged, the subjects had to answer whether they had seen precisely this picture earlier, whether they had seen a similar picture, or there was no such picture at all. The differences between the words "the same" and "similar" were exemplified before the performance of the experimental study. Only the subjects who understood the meaning of these words were subjected to investigation. The stimulus material at the recognition stage consisted of 30 pictures: 15 pictures identical to the sample, 10 pictures resembling the lateral stimuli in the triplets, and 5 new distractors.

Statistical data processing was carried out using the statistical programing language and the software environment *R* (www.r-project.org). Nonparametric Wilcoxon-Mann-Whitney test was used to assess the statistical significance of differences in the distribution of values in two groups. In order to analyze the relationship between two values, Spearman's correlation coefficient was calculated. The differences or relationship was considered to be statistically significant at a level of significance of $p = 0.05$.

RESULTS

The results of memorizing the material in the EAM Method are represented in Fig. 2. Both patients with focal brain lesions and healthy subjects made errors when they recalled the pictures. However, the nature of these errors in the clinical group and in the comparison group was different. In healthy subjects, forgetting did not exceed 25% of the initial information content. The procedures of free reproduction and recognition of the pictures were equally difficult: statistically significant correlation between the number of the objects named during free reproduction and the number of correct answers during stimulus recognition was revealed ($r = 0.6$; $p = 0.00001$). The share of unnamed objects and the percentage of errors during recognition were similar (Fig. 2a). The errors made in relation to lateral images in each triplet were additionally processed. We observed a similar number of errors in recognition of the left- and right-sided stimuli in healthy subjects (Fig. 2b).

In the clinical group, a considerable impairment of the memory indices depending on a tumor in the right or left hemisphere was observed compared with healthy subjects. When the left hemisphere of the brain was affected, the process of delayed free reproduction was more difficult than the process of picture recognition (Fig. 2a). Note that the stimuli arranged in the right side of the triplet were recognized and reproduced worse than those located on the left (Fig. 2b).

In patients with the right hemispheric involvement, the total number of unrecognized stimuli was virtually the same as in patients with a left hemispheric tumor,

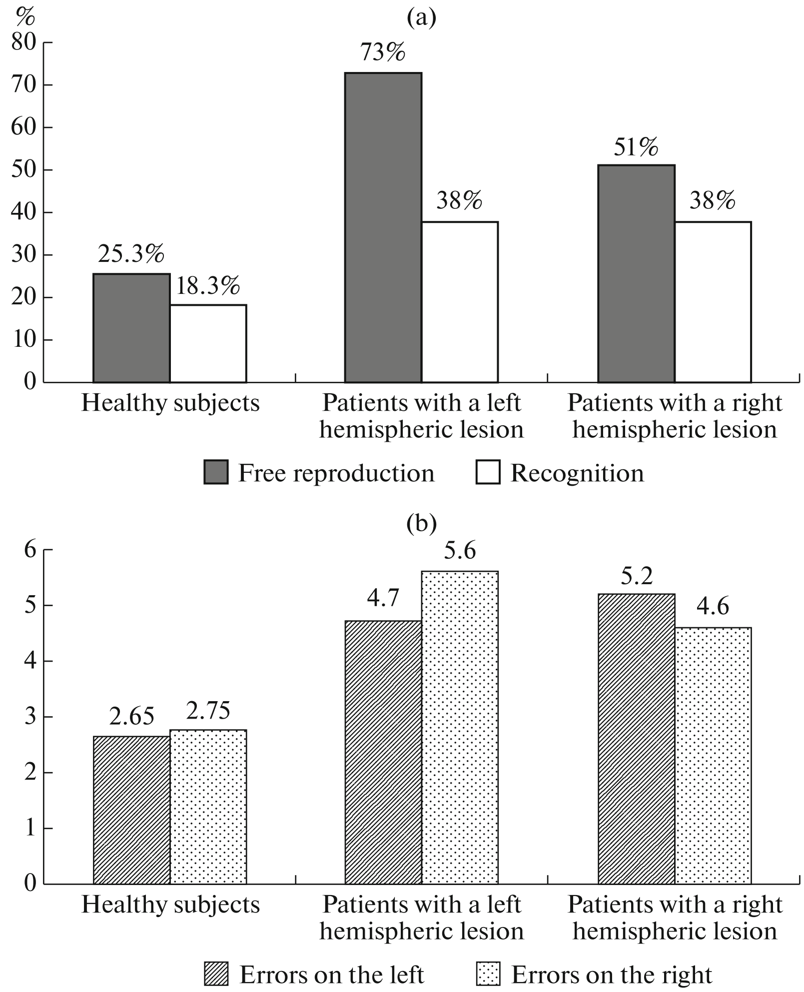

Fig. 2. Results of stimulus reproduction and recognition in the EAM method. (a) The share of not reproduced objects in the free reproduction test and the percentage of errors in the stimulus recognition test and (b) the average number of the errors of recognition of the triplet left stimuli (the left column in each pair) and the triplet right stimuli (the right column in each pair).

but free reproduction was significantly better than in patients with the left hemispheric damage (Fig. 2a). The most important result in the context of the analyzed problem was inverted distribution of errors in recognizing lateral stimuli compared with the left hemispheric group; here, there were more errors than in the left visual field (Fig. 2b).

Further analysis was connected with the study of the features of gaze movement. The number of visual fixations was calculated for each image in the triplet and compared with the results of its free reproduction and recognition. However, no relationship between these parameters was detected. The duration of looking at the pictures, which the subjects recalled in the free reproduction test (the medians of the number of fixations on each picture varied between 50 and 95), did not differ statistically significantly from the duration of looking at the pictures, which were not recalled upon free reproduction (the medians of visual fixations 42–85, $p > 0.05$). The same tendency was observed for recognized (the medians of visual fixations 48–99 for different stimuli) and unrecognized stimuli (the medians of visual fixations 50–80, $p > 0.05$).

Despite the fact that the results of memorizing did not depend on the number of visual fixations, they were definitely determined by the character of fixation patterns. The examples of the patterns are represented in Fig. 3. Table 1 shows the data on the results of memorizing in the subjects. The + sign in Table 1 marks the stages of the EAM Method the subjects underwent unerringly. For example, healthy subject F. (Fig. 3a) coped with all the stages error-free. He could recall the stimuli during free reproduction. Having seen the distractors resembling the stimuli he could say that these were precisely "similar" images (since similar images were not presented for the middle triplet stimuli, the recognition stage is absent for them). And, finally, seeing the original of the picture, he could identify the stimulus he tried to remember. In the case of errors

Table 1. Results of remembering for the examples represented in Fig. 3

	Subjects	The "apple" stimulus			The "turtle" stimulus		The "glasses" stimulus		
		verbal reproduction	recognition of a similar stimulus	recognition of the original	free reproduction	recognition of the original	verbal reproduction	recognition of a similar stimulus	recognition of the original
A	Healthy subject F. aged 23 years	+	+	+	+	+	+	+	+
B	Healthy subject G. aged 74 years	Did not recall	Absent	Absent	Did not recall	+	+	+	+
C	Patient R. aged 58 years. Tumor of the left temporal lobe	Did not recall	+	+	Did not recall	+	Did not recall	There was no such picture	Absent
D	Patient V. aged 32 years. Tumor of the right temporal lobe	+	+	"There was something similar"	Frog	Absent	+	There was such a picture	+
E	Patient S. aged 50 years. Tumor in the right parietal-temporal-occipital region	Did not recall	Absent	Absent	+	+	Did not recall	Absent	"There was something similar"

+, Correct answers of the subject. The words designate the variants of erroneous recall.

(the stimulus was neither recalled nor recognized correctly) Table 1 contains the word corresponding to the error. For example, healthy subject G. (Fig. 3b) did not remember the "apple" and "turtle" stimuli during free reproduction and gave the answer "there was no such picture" during presentation of the pictures with an apple (similar and the original).

The fixation patterns in subject F. are characterized by a high concentration at the center of the object or its important semantic areas. They are well-grouped and very economical in transition from one image to another. Searching eye movements in the subject are virtually absent. Figuratively speaking, it is a watchful, steadfast, and maximally attentive gaze. Such fixation patterns in our study led, as a rule, to complete, error-free reproduction and recognition of the objects.

A different fixation pattern was observed for these stimuli in subject G. (Fig. 3b). Only the "glasses" stimulus causes the gaze to be fixed on the center of the image. This stimulus is subsequently reproduced and recognized. You would think the subject was looking at the "apple" stimulus, but the gaze sort of missed the target; many fixations are at the sides of the stimulus. It is an absent look followed by the subsequent stimulus neglect and the absence of information about it in the subject's memory.

In patients with focal cerebral lesions, both fixations similar to the patterns of healthy individuals and specific fixations that do not occur in normal attention allocation were observed. Pathological variants of the patterns were more often observed in relation to the stimuli contralateral to the affected hemisphere.

In patient R. with a tumor in the left temporal lobe (Fig. 3b), we observed many superfluous gaze movements in the empty exposition regions. The gaze cannot be called concentrated; many fixations miss the target. In fact, the "glasses" stimulus remains without visual fixations. The gaze travels to the right part of the triplet but hits below the stimulus. As a result, the stimulus is not retained in memory: it is neither reproduced nor recognized. It may be said that the stimulus is already neglected at the stage of attention allocation.

Patient V. with a tumor in the right temporal lobe (Fig. 3d) exhibited a large number of searching, sweeping gaze movements as if they were scanning all the exposure space without fixation on any image and without its careful and close examination. As a result, the patient is able to notice all the pictures and to name two of them correctly from memory. But she has no time to see all the details. No specific visual object of the image is formed. Recalling that there was "something green" at the center, she calls the stimulus a "frog". She makes errors in relation to all the stimuli at the recognition stages.

Patient S. with a tumor in the right parietal-temporal-occipital region is diagnosed as having fixed left-sided agnosia (Fig. 3d) during neuropsychological investigation. When the triplet is scrutinized, all visual fixations are on the middle stimulus. Note that, as distinct from most subjects who anyway fixed their gaze

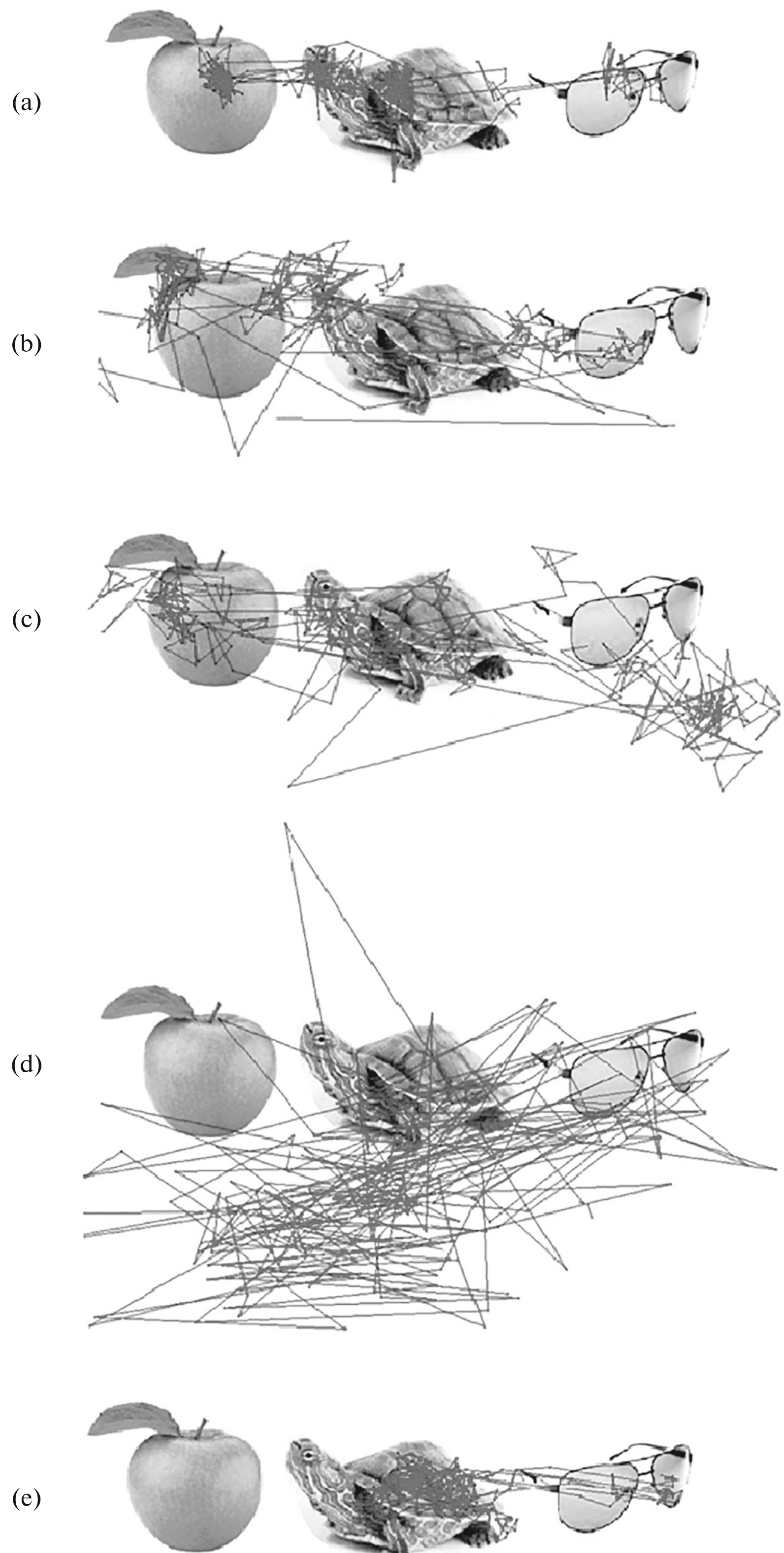

Fig. 3. Eye movement trajectories in remembering the stimuli in different subjects. Explanation is in text.

on the head of a turtle, she does not move hers to the left part of the image. However, the "turtle" stimulus is recalled during free reproduction and recognized upon identification. The patient did not remember the "glasses" stimulus, to which the fixation pattern was partly distributed, but admitted its presence in the course of recognition: when she was presented the original, she said that she had seen similar glasses when memorizing. The left "apple" stimulus is absolutely ignored—the gaze is not fixed on it—the object is not remembered, and its presence during recognition is not admitted.

DISCUSSION

The study provides confirmation of heterogeneous attention allocation in space and dependence of realized and remembered information on this attention characteristic and the features of interhemispheric interaction in its support.

After the period of interference, the participants in the study had to recall the pictures presented for 10 s and to name them in any order with any words they thought were suitable. According to the literature data, this process is predominantly connected with the functional activity of the left hemisphere of the brain [3, 16]. True, the task of free reproduction (naming) of the stimulus material caused the greatest difficulties in patients with left hemispheric lesions. A severe impairment of free reproduction under the EAM method conditions in patients with left hemispheric lesions is supposedly linked to decreased total effectiveness of speech-related associative processes, which, even in the absence of the aphasic pathology proper, made the task maximally sensitized for patients with left hemispheric affection.

The data showing that the subsequent differentiation between a stimulus image and similar objects requires careful scrutinizing and an effective pattern of visual fixations were obtained in the study. This process is disturbed by damage to both the left and the right hemisphere without clear lateral differences in its overall effectiveness (certain partial features determined by localization of the focus were detected, but they are outside the scope of this work).

The character of visual patterns allows us to foresee the possibility of the subsequent recall of a stimulus in both healthy subjects and patients with focal brain lesions. In the absence of special terminology for describing the patterns of visual fixations, the words of everyday language were used.

Effective patterns. The gaze hits the target; fixations are well-grouped at the center of an object or in its important semantic areas. Economical gaze movement from stimulus to stimulus. Random gaze movements in the empty exposure regions are hardly present. Good attention concentration; a grasping steadfast gaze.

Ineffective patterns. Sweeping eye movements across the exposed area, as though they were searching and controlled by the task to find something, to answer the "where" question. Many superfluous movements from stimulus to stimulus. Many fixations missing the target, somewhere at the side, somewhere in an irrelevant random place, sometimes in an empty space. Absent look, wandering eyes. It could be suggested that at this moment, the subject's attention is being focused on his or her thoughts rather than on the stimuli.

The strategy of scrutinizing the triplets is not always identical in the same subject even within the framework of one experimental session. For example, against the background of complete reproduction and exact recognition of the stimuli of four triplets, the fifth set could be absolutely forgotten or associated with recognition errors. These time-dependent variations in attention were described in sufficient detail in the literature [1]. The work was devoted to nonuniform attention allocation in space. The stimuli contralateral to the focus of lesion were reproduced and recognized less accurately than those located ipsilaterally. Ineffective patterns of visual fixations were more often observed in the visual field contralateral to the focus.

Probably, an extreme and the most marked manifestation of inattention to a stimulus is its neglect. The stimulus ceases to exist in the human memory. The subject does not recall it during free reproduction, and when he sees it in the pictures, he answers that he has not seen anything even vaguely resembling the stimulus during exposure. Of three pictures arranged nearby, one is not given allocated attention. As seen in Fig. 3e, the left stimulus in patient with a tumor in the right hemispheric parietal-temporal-occipital region was not accompanied by visual fixations. This is a typical pattern of fixed left-sided agnosia [3, 7]. However, the stimulus neglect phenomenon was also observed in the situations accompanied by visual fixations. In Figs. 3b and 3c, one can see the examples of fixations of a healthy subject (the left stimulus is ignored) and a patient with the affection of the left temporal lobe (the right stimulus is neglected). The study showed that the phenomenon of neglect may be observed not only in the situations of complete absence of visual fixations on the object but also in cases of ineffective patterns.

The use of the data obtained in the rehabilitation of patients with gnostic disorders is a clinical interpretation of the studies of attention. The techniques of correction based on attention reallocation were described in the monograph by Khrakovskaya [17]. Attempts are being made to modulate attention with a system of virtual reality [18]. Eye tracking is used to attract attention in patients with a severe decrease in overall spontaneity [19]. The rehabilitation context of the subsequent works must contain the thought repeatedly pronounced by N.N. Traugott in her works that understanding the mechanisms of a disorder and investigation of the nature of the defect are the main steps along the pathway to restoration of a mental process.

CONCLUSIONS

Spatial attention allocation may be objectified by recording human eye movements. Visual information perception and remembering depend on the patterns of visual fixations. Concentrated on the identifying features of an image, visual fixations contribute to information storage in memory. Random, scattered fixations do not often appear to be effective, especially in differentiation between similar images. A focal brain lesion results in decreased attention at contralateral side. Here, more reproduction and recognition errors and less effective patterns of visual fixations are observed compared with the ipsilateral side. Stimulus neglect is an extreme manifestation of disturbed spatial attention allocation—this stimulus will not be reproduced and recognized later. This neglect is observed both in the absence of visual fixations on a stimulus and in combination with ineffective patterns.

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