ISSN 0362-1197, Human Physiology, 2017, Vol. 43, No. 2, pp. 184–190. © Pleiades Publishing, Inc., 2017.
Original Russian Text © D.V. Zakharchenko, V.B. Dorokhov, V.I. Torshin, D.S. Sveshnikov, I.L. Myasnikov, V.V. Dementienko, 2017, published in Fiziologiya Cheloveka, 2017, Vol. 43, No. 2, pp. 74–81.

# Method for Noninvasive Diagnosis of Functional State Disorders in Operators with the Smooth Pursuit Test

**D. V. Zakharchenko[a, *], V. B. Dorokhov[a], V. I. Torshin[b], D. S. Sveshnikov[b], I. L. Myasnikov[b], and V. V. Dementienko[c]**

[a] *Institute of Higher Nervous Activity and Neurophysiology, Russian Academy of Sciences, Moscow, Russia*
[b] *People's Friendship University of Russia, Moscow, Russia*
[c] *Kotel'nikov Institute of Radioengineering and Electronics, Russian Academy of Sciences, Moscow, Russia*
**e-mail: dz-ihna@mail.ru*

Received November 26, 2015

**Abstract**—The article describes a videooculographic method to detect functional state disorders in operators in the target tracking test. The method is an improved version of the smooth pursuit test and can be used to detect and to estimate the effects of various adverse factors on operators in laboratory experiments. The method is noninvasive, allows a continuous data recording for a long period of time with the subject in comfortable conditions, and may employ various videooculographic devices (including portable and low-cost models). As an example, a series of experiments was performed to detect the negative effects of alcohol intoxication. A linear relationship was observed between changes in parameters of oculomotor reactions and changes in reaction time to the target stimulus.

*Keywords:* videooculography, eye-tracking, target, saccade, fixation, alcohol, operator, functional state, visual perception, smooth pursuit

**DOI:** 10.1134/S0362119717010091

## INTRODUCTION

Studies of oculomotor reactions during operations have been among the most in-demand areas in terms of their applied significance over the past 15 years. Particular interest focuses on the oculomotor activity parameters that are suitable for continuously monitoring and checking the state of operators and drivers in the course of their activities [1–3]. However, in spite of ample studies and findings, there is still no oculographic criterion that would report abnormalities of the operator's state and would allow automated real-time diagnosis of the operator's state [3, 4].

The smooth pursuit test and its versions have been widely employed in diagnosing various diseases and abnormal conditions unrelated to organic pathology for many years. The smooth pursuit test has provided a basis for developing methods to diagnose schizophrenia [5–9], manic depressive disorder [10], certain psychoses [11], epilepsy [12], autism [13], Alzheimer's disease [14], and Parkinson's disease [15–18]. Attempts have been made to adapt the test for studying monotonous activity and falling asleep [19]. Further modification of the smooth pursuit test is necessary because the methodical opportunities of videooculography are still not used in full (in particular, this is so with the opportunities to record the data for a long period of time or to perform experiments in conditions maximally close to those of real activities). In addition, ergonomics of the experimental procedure has substantial drawbacks (e.g., ophthalmological devices are used to fix the subject's head position). The conventional method to estimate the accuracy of target tracking is questionable: the discrepancy between the gaze and target trajectories and its changes with time usually serve to characterize the tracking accuracy; the distance is measured between each point of the gaze trajectory and the respective point of the target trajectory, and changes in distance are used to infer the tracking accuracy. The question as to whether the method is correct arises because the gaze coordinates are impossible to align with the display coordinates to accuracy higher than $\pm 0.5$ angular degrees. A substantial part of the effects conventionally employed in diagnosis (jerk patterns, tracking delays, anticipatory saccades, saccades directed away from the trajectory, etc.) consequently fall in a range of $\pm 0.5$ angular degrees of gaze coordinate measurements and are interpreted as recording noise.

The objective of this work was to develop a method for assessing the operator's function state such that has all advantages of the smooth pursuit test and makes it possible to record oculographic data in conditions similar to those of real activities. The method should additionally allow experiments of various durations,

and the algorithm used to assess the subject's state should be low sensitive to micromovements of the subject's head during the test.

Modified smooth pursue test can be used in a laboratory setting to diagnose the effects of various factors on an operator's performance. Several basic changes were made to the conventional smooth pursuit test to modify both the test procedure and data treatment methods.

(1) *We rejected head fixation with an ophthalmological head restraint system*.

The head position is fixed from behind by using a headrest. This approach allowed us to greatly increase the record duration (from 3–5 to 15 min and further) and thereby to avoid the warm-up effect in early testing (the first 1–2 min) and to substantially reduce the effect of the experimental situation on test performance (because the subject is in comfortable conditions close to a natural situation).

(2) *We evaluate how smoothly, rather than how accurately, the target is pursued with the gaze*.

When eye tracking is carried out for more than 2–3 min, the recording accuracy appreciably decreases because of micromovements of the subject's head (even when the head is fixed with a head restrain device). If the tracking accuracy is used to evaluate the subject's state, the calibration error can increases so dramatically after 2–3 min that the experiment has to be terminated. The maximal record duration is therefore restricted to few minutes. If smoothness, rather than accuracy, of tracking is estimated, the calibration error has absolutely no effect on the parameter under study because aligning the gaze coordinates with the display coordinates is not critical for estimating how smooth the tracking is. Thus, the experiment can continue as long as necessary and without rigid fixation of the subject's head (that is, in conditions that are natural to the subject). In addition, our approach abolishes the effect of recording errors due to micromovements of the subject's head in the course of the experiment.

(3) *A circular target trajectory is used in place of the conventional sinusoid trajectory.*

The change makes the target trajectory uniform. This simplifies data analysis and interpretation and abolishes the oculomotor effects associated with target tracking at the extrema of a sinusoid trajectory. In addition, our psychomotor test allows the testing conditions to be maximally close to the conditions of the operator's actual activity.

To demonstrate the efficiency of our method in diagnosing and evaluating abnormal states in operators, here we report the testing results obtained for 22 subjects before and after alcohol drinking.

## METHODS

The study involved 22 male volunteers aged from 20 to 36 years. All subjects were physically healthy and denied alcohol abuse. The first selection step was performed through the Internet and included providing information about the test procedures and instructions (to have enough sleep; not to take alcohol, coffee, and drugs on the day of testing and one day before testing; to have a meal 2 hours before testing). The subjects received payment for their participation. All subjects agreeing to participate in the experiment had sufficient experience in working with a computer and a mouse and were motivated enough to perform the test tasks. The second selection step was carried out on the day of testing and included providing information about the test task and recording a pilot videooculogram.

**Experimental model of alcohol intoxication.** In an experimental model of alcohol intoxication, the subjects took alcohol at 0.8 g of 96% alcohol per 1 kg body weight; the alcohol amount was expressed in terms of 40% vodka. The alcohol content in expired air was measured with an AL-7000 breath alcohol tester at an accuracy of ±15% of the measurement (prior to, in the middle, and at the end of an experimental series). With due regard to the time course of alcohol assimilation, the subject conversed with the investigator on irrelevant topics for 1 hour after drinking alcohol, and then the test started.

**Physiological data recording.** Oculomotor reactions of the subjects were the main physiological parameter in our study. A gaze trajectory was recorded with an Eyegaze Analysis System (hereafter referred to as an eye-tracker), which allows video-based detection of eye movements in a contactless manner and utilizes the infrared light reflection from the cornea, and NYAN 2 softwar (Interactive Minds). Data were recorded in a binocular mode with a sampling rate of 120 Hz, a distance to the display of 60 cm, display resolution of 1280 × 1024 pixels, and a pixel size of 0.265 mm (an angular displacement of a target on the display by 1 pixel approximately corresponded to a displacement by 0.0246° relative to the subject's eye in this experiment). The subject's head was fixed from behind with a headrest.

**Psychomotor test.** To simulate target-tracking activity of an operator, we designed a psychomotor test (Fig. 1). The software of this test allows to perform a visual and a visual-motor target tracking and can register the parameters of the moving target and visuomotor reactions. The test was presented in a darkened room, using a Samsung 17" liquid-crystal display (340 × 27 mm, resolution 1280 × 1024 pixels). We recorded the trajectory of mouse cursor movements on the display, all clicks of mouse buttons, and related actions on the display (appearance, movement, and disappearance of test stimuli). The sampling interval was 8 ms (125 Hz).

In the test, a main target (a green circle with a diameter of 8 mm) moved along a circular trajectory of 75 mm in diameter with an angular velocity of 28°/s relative to the center of the display. Once in 3–7 s, an

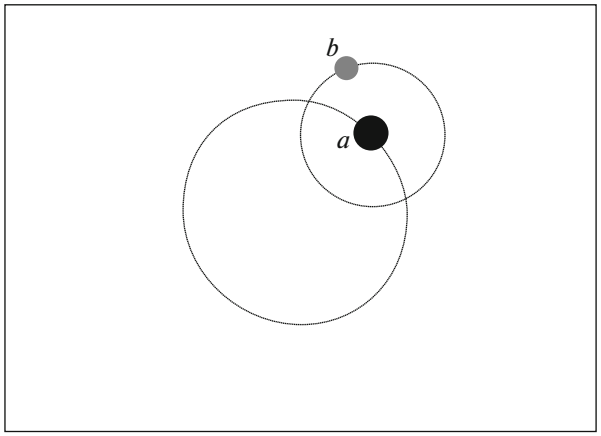


**Fig. 1.** Pychomotor test: trajectories of (*a*) the main and (*b*) additional targets. Both targets move clockwise. The trajectories are not displayed when testing a subject.

additional target (a red circle of 12 mm in diameter) appeared on the outer side of the trajectory. The additional target started orbiting around the main target with an angular velocity of 29°/s. The orbiting radius of the additional target was 60 mm. The subject was instructed to track the main target with the mouse cursor and to keep the cursor within its boundaries. When the additional target appeared, the subject had to click on the main target (which he was tracking). The additional target served to provide a signal and disappeared after a click on the main target. A total of 150–180 additional targets were presented in the course of the test; the interval between additional target presentations varied from 3 to 7 s at random.

**Procedure of the study (experiment).** The study procedure included two, control and experimental, tests. The control test was performed first. The subject sat down in a chair; the eye-tracker was calibrated; and the subject performed the psychomotor test for 15 min. Then the subject moved to another room, took alcohol, and conversed with the investigator on irrelevant topics for 1 hour (an interval between the control and experimental tests was made to allow alcohol to assimilate and to avoid the stimulating effect). One hour after alcohol drinking, the alcohol content in expired air was measured and the experimental test was performed exactly as above.

## RESULTS

To evaluate how smoothly the target is tracked visually, we analyzed the gaze trajectories recorded in the psychomotor test prior to and after alcohol intake. Specifics of the gaze trajectories are clearly seen on their images (Fig. 2). In the control test (Fig. 2a), the target was tracked smoothly, there were almost no jerks and prolonged fixations, and only minor deviations (usually no greater than 1–1.5 angular degrees) from the target trajectory were observed. After alcohol

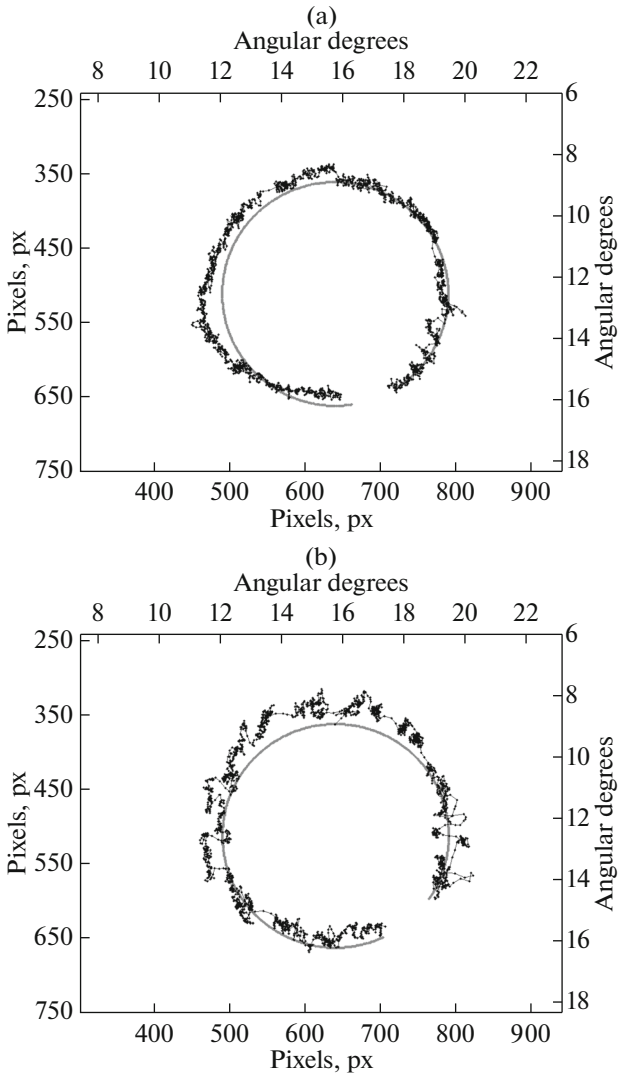


**Fig. 2.** Changes in the pattern of target tracking with gaze after alcohol intake. Subject 20; time interval from second 59 to second 66 of the experiment. The target trajectory is shown gray; the gaze trajectory, black. Target tracking was performed (a) before and (b) after taking alcohol.

intake (Fig. 2b), the gaze trajectory was no longer smooth, prolonged fixations and jerks were seen (including those perpendicular to the target trajectory) along with backward movements, and saccades and rapid drift events increased in number.

The following algorithm was used to quantitatively estimate the smoothness of a gaze trajectory.

(1) The gaze trajectory was smoothed using a digital filter (to remove the high-frequency component of more than 0.2 Hz) and adjusted by phase. The procedure yielded a smoothed gaze trajectory, which is an approximating curve (Fig. 3).

(2) The distance in pixels was calculated for each point of the actual (unsmoothed) gaze trajectory and the corresponding point of the smoothed trajectory. A

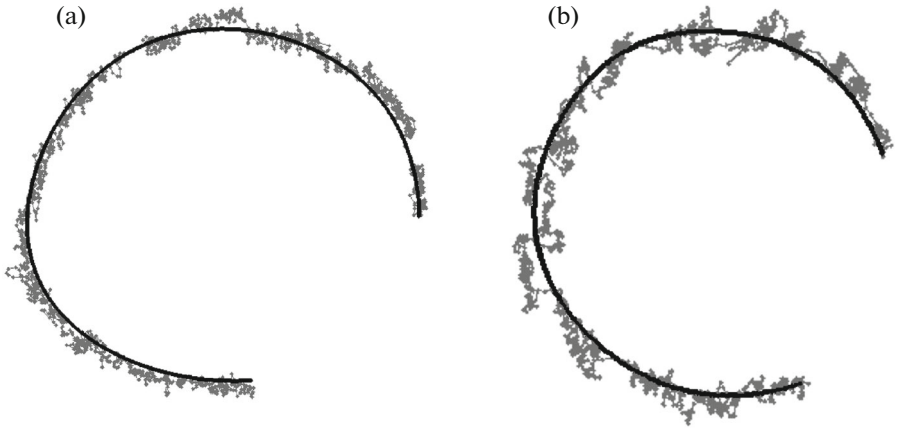


**Fig. 3.** Approximating curves (a) before and (b) after alcohol intake. The gaze trajectory is shown gray; the approximating curve, black.

sequence of deviations from the approximating curve was thus obtained with each point of the trajectory[1].

(3) The resulting sequence of deviations was visualized (Fig. 4) and analyzed statistically.

The algorithm is based on the idea that a deficiency in target tracking would increase the mean deviation from the approximating curve. If the trajectory becomes less smooth indeed after alcohol intake, while the data set size remains the same, then differences should be clearly seen in a histogram of deviations (Fig. 4a).

A typical distribution (15 out of the 22 subjects) of deviations between the actual trajectory and the approximating curve is shown in Fig. 4a. Substantial changes in distribution shape were seen after alcohol intake, i.e., the mode was slightly shifted toward higher values, the mode amplitude decreased greatly, the peak was less sharp, and the right part of the distribution showed a lower slope. The changes were characteristic of the subjects who displayed tracking deficiency after taking alcohol.

Atypical shapes of the deviation distribution are shown in Figs. 4c and 4d. In one case, the distribution remained almost unchanged (Fig. 4c), suggesting no change in the smoothness of target tracking. In the other case (Fig. 4d), the changes were opposite to those observed typically; i.e., the smoothness slightly increased. The atypical distributions had low frequencies each (3 and 4 out of the 22 subjects, respectively), but together accounted for one-third of the sample.

As is well seen from the histograms, the mode amplitude changed most distinctly after alcohol intake. The normalized mode amplitude was used as a main parameter in a quantitative analysis of the smoothness of target tracking. To calculate this parameter, the histogram data was first smoothed by the simple moving average method with a period of 3. Smoothing was carried out in two steps: from the start to the end of the variation series and then from the end to the start. This approach provides for high quality of smoothing and helps to avoid a phase displacement (Fig. 4b). Then we did the normalization of the mode amplitude for both sets of data: prior to and after alcohol intake. To normalize, the mode amplitude was divided by the number of measurements (data rows) in the data set. The normalized mode amplitude can be used as a quantitative parameter that shows how smooth the tracking is. The normalized mode amplitude values obtained prior to and after alcohol intake were compared in all subjects by the sign test and the Wilcoxon matched pairs tests. The normalized mode amplitude values was found to decrease at a high probability ($p = 0.001384$ in the sign test and $p = 0.003302$ in the Wilcoxon matched pairs test). Thus, smoothness of the gaze tracking of the target typically decreased after alcohol intake.

Time to hitting a target was the only behavioral parameter that was assessed in the psychomotor test. Alcohol intake significantly increased the response time (the time to hitting a target), the significance of changes being extremely high ($p = 0.000014$ in Student's paired sample $t$-test).

## DISCUSSION

As our results show, our method is highly efficient in detecting the effect of an adverse factor (alcohol intoxication in our case) on an operator's performance. To demonstrate that the intensity of the effect is also possible to evaluate, we compared the changes in smooth target tracking (as inferred from the normalized mode amplitude) with the decrease in operator performance (as inferred from the response time to an additional stimulus in the psychomotor test).

[1] Calculating the distances between each point of the unsmoothed gaze trajectory to the corresponding point of the approximating curve is essentially similar to eliminating the low-frequency data component (trend), which is uninformative and has no effect on the tracking smoothness estimate.

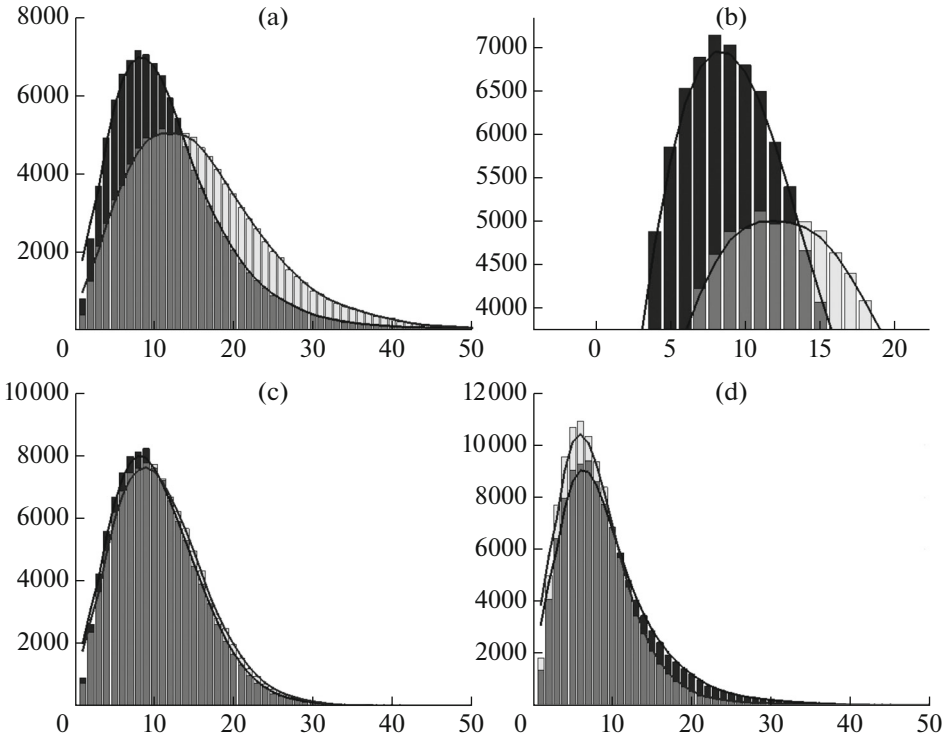


**Fig. 4.** Alcohol-induced changes in the deviation of the actual trajectory from the approximating curve. Data were collected before (dark gray histogram) and after (light gray histogram) alcohol intake. (a) The most typical distribution shape (15 out of the 22 subjects); (b) envelope curve fitting to calculate the mode amplitude; (c, d) atypical distribution shapes (4 and 3 out of the 22 subjects, respectively).

A relationship between the response time of an operator (abscissa) and the change in smooth tracking (normalized mode amplitude, ordinate) is shown in Fig. 5. It should be noted that the plot shows the difference between two measurements (prior to alcohol taking – before alcohol taking) rather than the measurements themselves. Each point shows the data obtained for one subject. The area where responses were atypical for the sample and might be considered artefactual is shown gray.

The distribution of points in open area (responses typical for the sample) can be interpreted as follows. Separation is clearly seen for a group of subjects that displayed a strong correlation between an increase in reaction time and a decrease in smooth target tracking (inferred from normalized mode amplitude). The group is shown with an oval. The coefficient of correlation between the two parameters was high, –0.88 at $p < 0.00005$ for Pearson rank correlation and –0.84 at $p < 0.0001$ for Spearman rank correlation. The effect of alcohol on these subjects was typical of the sample; the dependence between a decrease in smooth tracking and an increase in reaction time is described by a simple linear function. The subjects not included in this group displayed a minor decrease in smooth tracking (normalized mode amplitude). We think that the effect of alcohol in these subjects was not strong enough to distort their ability to perform simple motor operations. A presumable smoothness threshold below which behavioral alterations start to be detectable is shown with line *b* in Fig. 5.

Thus, our method makes it possible to detect alterations in operator performance and to quantitatively evaluate their intensity by analyzing the smooth pursuit test data. The time of a continuous recording of oculomotor reactions can be increased to at least 15 min with our method, and testing can be performed in conditions maximally similar to actual operation conditions. The procedure does not involve any discomfort to the subject, nor does it require an ophthalmological head restrain device.

## CONCLUSIONS

(1) The dependence between a decrease in tracking smoothness and an increase in reaction time after taking alcohol is linear, but is seen only when alcohol substantially affects the subject's state and the subject is inadequate.

(2) A change in the smoothness of target tracking with gaze is a marker of a decrease in operator performance and can be used to predict operator performance disorders.

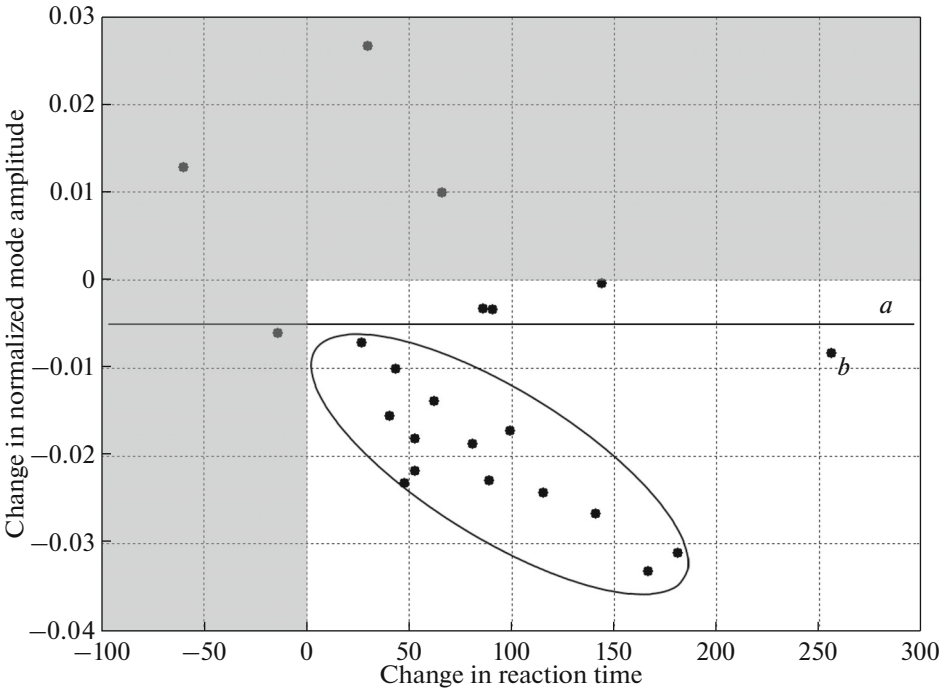


**Fig. 5.** Alcohol-induced changes in tracking smoothness and reaction time. Abscissa, change in average reaction time (ms), that is, the difference between the reaction times obtained after and prior to alcohol uptake. Ordinate, change in normalized mode amplitude (tracking smoothness). The parameter is dimensionless and is obtained as a difference between the mode amplitudes obtained after and prior to alcohol intake. Gray area, reactions atypical for the sample; *a*, presumable threshold for a decrease in tracking smoothness at which the subject still preserves the normal operation performance; *b*, outlier.

## ACKNOWLEDGMENTS

This work was supported by the Russian Humanitarian Science Foundation (project no. 14-06-00652 “Changes in Parameters of Visual-Motor Coordination in Response to Alcohol in Operators and Drivers”).

## REFERENCES

1. Hartley, L., Horberry, T., and Mabbot, N., *Review of Fatigue Detection and Prediction Technologies. National Road Transport Commission*, Melbourne, 2000.
2. Dorrian, J., Lamond, N., Kozuchowski, K., and Dawson, D., The driver vigilance telemetric control system (DVTCS): investigating sensitivity to experimentally induced sleep loss and fatigue, *Behav. Res. Methods*, 2008, vol. 40, no. 4, p. 1016.
3. Kerick, S., Metcalfe, J., Feng, T., et al., *Review of Fatigue Management Technologies for Enhanced Military Vehicle Safety and Performance*, Army Research Laboratory, Aberdeen Proving Ground, USA, 2013.
4. Wright, N., Stone, B., Horberry, T., et al., A review of in-vehicle sleepiness detection devices, in *Published Project Report PPR157*, TRL Limited, 2007.
5. Franco, J.G., de Pablo, J., Gaviria, A.M., et al., Smooth pursuit eye movements and schizophrenia: Literature review, *Arch. Soc. Esp. Oftalmol.*, 2014, vol. 89, no. 9, p. 361.
6. Spering, M., Dias, E.C., Sanchez, J.L., et al., Efference copy failure during smooth pursuit eye movements in schizophrenia, *J. Neurosci.*, 2013, vol. 33, no. 29, p. 11779.
7. Levy, D.L., Sereno, A.B., Gooding, D.C., and O’Driscoll, G.A., Eye tracking dysfunction in schizophrenia: characterization and pathophysiology, *Behav. Neurobiol. Schizophr. Treat.*, 2010, vol. 4, p. 311.
8. Mialet, J.P. and Pichot, P., Eye-tracking patterns in schizophrenia: an analysis based on the incidence of saccades, *Arch. Gen. Psychiatry*, 1981, vol. 38, no. 2, p. 183.
9. Avila, M.T., Sherr, J.D., Hong, E., et al., Effects of nicotine on leading saccades during smooth pursuit eye movements in smokers and nonsmokers with schizophrenia, *Neuropsychopharmacology*, 2003, vol. 28, no. 12, p. 2184.
10. Lipton, R.B., Levin, S., and Holzman, P.S., Horizontal and vertical pursuit eye movements, the oculocephalic reflex, and the functional psychoses, *Psychiatry Res.*, 1980, vol. 3, no. 2, p. 193.
11. Holzman, P.S. and Levy, D.L., Smooth pursuit eye movements and functional psychoses, *Schizophr. Bull.*, 1977, vol. 3, no. 1, p. 15.
12. Bittencourt, P.R., Gresty, M.A., and Richens, A., Quantitative assessment of smooth-pursuit eye movements in healthy and epileptic subjects, *J. Neurol., Neurosurg. Psychiatry*, 1980, vol. 43, no. 12, p. 1119.
13. Wilkes, B., Carson, T., Patel, K., et al., Oculomotor performance in children with high-functioning Autism

Spectrum Disorders, *Res. Dev. Disabil.*, 2015, vol. 38, p. 338.

14. Molitor, R.J., Ko, P.C., and Ally, B.A., Eye movements in Alzheimer's disease, *J. Alzheimer's Dis.*, 2015, vol. 44, no. 1, p. 1.
15. Fukushima, K., Ito, N., Barnes, G.R., et al., Impaired smooth-pursuit in Parkinson's disease: normal cue-information memory, but dysfunction of extra-retinal mechanisms for pursuit preparation and execution, *Physiol. Rep.*, 2015, vol. 1, no. 3, p. 1.
16. Jansson, D., Medvedev, A., Axelson, H., and Nyholm, D., Stochastic anomaly detection in eye-tracking data for quantification of motor symptoms in Parkinson's disease, *Adv. Exp. Med. Biol.*, 2015, vol. 823, p. 63.
17. Lemos, J. and Eggenberger, E., Saccadic intrusions: review and update, *Curr. Opin. Neurol.*, 2013, vol. 26, no. 1, p. 59.
18. Nilsson, M.H., Patel, M., Rehncrona, S., et al., Subthalamic deep brain stimulation improves smooth pursuit and saccade performance in patients with Parkinson's disease, *J. Neuroeng. Rehabil.*, 2013, vol. 10, no. 1, p. 33.
19. Dorokhov, V.B., Arsen'ev, G.N., Tkachenko, O.N., et al., The psychomotor test for research of eye-hand coordination at performance of monotonous activity on tracking target, *Zh. Vyssh. Nervn. Deyat. im. I. P. Pavlova*, 2011, vol. 61, no. 4, p. 476.

*Translated by T. Tkacheva*