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Prediction of the Moments at which Critical Decreases in Levels of Arousal Occur Using Visuomotor Coordination Parameters

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A psychomotor test allowing the state of monotony to be modeled and changes in visuomotor coordination to be followed during decreases in the level of arousal was developed. The subjectsl task was to use a mouse cursor to follow a target moving slowly on a monitor screen in a circular orbit and to respond to an unexpected novel stimulus by moving the cursor to it and pressing the mouse button; the test lasted 1 h. Throughout the experiment, visuomotor coordination parameters were recorded: the latent periods of gaze and mouse cursor displacement and the latent period of pressing the mouse button in response to the appearance of the novel stimulus, as well as deviations of gaze and the mouse cursor from the center of the target, which characterize target tracking accuracy. EEG and video imaging of the subjects were used for expert evaluation of changes in the level of arousal. Visuomotor coordination parameters were found to be highly sensitive to changes in the level of arousal. Decreases in the level of arousal were accompanied by increases in the latent periods of saccadic eye movements, mouse cursor movements, and pressing the mouse button, as well as variability in deviations of gaze and the mouse cursor from the center of the target. The latent periods of saccades, the onset of cursor movement, and mouse button pressing demonstrated significant increases at 2–3 min from the moment at which the expert noted a reduction in the level of arousal. The possibility of predicting the moments of critical reductions in the level of arousal using visuomotor coordination parameters is discussed.

Keywords: visuomotor coordination, monotony, saccades, tracking eye movements, microsleep, drowsiness, reaction speed.

Levels of attention in humans during tasks can very over a wide range, to the extent of involuntary falling asleep for a few seconds – these "gaps" intasks are termed episodes of microsleep. At these moments, humans show either significant increases in reaction times or complete failures to respond to external stimuli [Boyle et al., 2008]. It has been suggested that episodes of microsleep arise on the background of increasing drowsiness due to extreme activation of sleep-triggering mechanisms [Saper et al., 2010]. At these moments, changes in the nature of task performance are so sudden and unpredictable that some authors have suggested the hypothesis that a state of instability arises when the level of arousal decreases [Gunzelmann et al., 2009; Zhou et al., 2011]. In a variety of professional spheres, especially while driving vehicles, this instability of attention can have the most dramatic consequences [Dorokhov, 2013].

Drowsiness, a decrease in the level of arousal, occurs for various reasons and is mainly associated with sleep deficiency and time of day (the circadian rhythm). However, drowsiness also develops during performance of monotonous and boring work with low levels of external stimulation. In this situation, the cause of the decrease in the level of arousal is the state of monotony [Dorokhov, 2003]. Some authors have suggested that monotony reveals significant "masked" latent drowsiness, which occurs at the low levels of stimulation characteristic of monotony [Carskadon and Dement, 1987].

Elevated daytime drowsiness is a complex phenomenon which can be apparent as a prolonged and continuous

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state of somnolence or as sudden "sleep attacks." Furthermore, elevated drowsiness may result from a number of disorders: obstructive apnea syndrome, narcolepsy, and neurodegenerative diseases, including Parkinson's disease [Iranzo, 2011]. For example, about 50% of Parkinson's disease patients complain of elevated daytime drowsiness [Ondo et al., 2001; Shpirer et al., 2006]. Increased levels of drowsiness are sometimes among the few early symptoms of a number of neurological diseases and may provide an important diagnostic sign allowing diseases to be detected at an early stage. In particular, some authors [Abbott et al., 2005] believe that the risk of Parkinson's disease in patients developing increased daytime drowsiness increases by a factor of 2–3.

There is currently a lack of reliable and universal methods for monitoring the level of arousal [Dementienko and Dorokhov, 2013; Dementienko et al., 2006; Balkin et al., 2011; Whitlock, 2002]. The search for methodological approaches for objective evaluation of the level of arousal and the possibility of predicting decreases constitutes a relevant task both in medicine and safety at work.

The most direct means of assessing attention and its impairments is to record eye movements and determine the duration and dynamics of gaze displacement [Velichkovskii, 2003; Kolesnikova et al., 2006; Shul'govskii et al., 2008]. Oculomotor monitoring of moving objects involves two types of eye movements: saccades and tracking movements [De Xivry et al., 2006; De Xivry et al., 2007]. Optimum perception of an object, especially a moving object, requires fine coordination between the two types of movement [De Xivry et al., 2006]. Video tracking methods, which allow contactless recording of eye movements, are regarded as the technology with the greatest potential for creating instruments for monitoring the level of arousal in humans driving vehicles and operating machinery [Dementienko and Dorokhov, 2013].

Studies in our laboratory have included development of a psychomotor test for analyzing impairments to visuomotor coordination induced by decreases in the level of arousal [Dorokhov et al., 2011]. The aims of the present work were to identify whether this method can be used to predict the onset of a low-arousal state before task performance precision decreases and to identify which parameters of visuomotor coordination are most sensitive to decreases in the level of arousal. The preceding study [Dorokhov et al., 2011] showed that the psychomotor test developed here induced, at 25–40 min, a state of monotony in all subjects tested, this being apparent as a reduction in task performance precision, half of the subjects also showing moments of microsleep followed by the occurrence of profound errors. In the present study we exposed subjects to partial sleep deprivation (50%) such that a critical decrease in the level of arousal was induced all participants.

Methods

A total of 19 subjects of both genders, aged 21–30 years, took part in the study. Experiments were performed in the second half of the day (from 13:00 to 18:00). All subjects had at least three years of experience of using computers and confidently operated a computer mouse. Participants in the experiment were essentially healthy, with no complaints relating to sleep; all were subjected to partial sleep deprivation before the experiment, losing 50% of the duration of their usual night-time sleep. Subjects were familiarized with the experimental procedure and provided signed consent to take part. Levels of drowsiness were tested before the experiment, using the Epworth Sleepiness Scale [Johns, 1991].

The state of monotony was modeled using a method developed in our laboratory [Dorokhov et al., 2011]. Subjects had to use a computer mouse cursor to track a target moving slowly and uniformly across the screen in a circular orbit. As demonstrated previously [Dorokhov et al., 2011], this long-term and uniform activity induced the state of monotony and a decrease in the level of arousal.

The circular orbit along which the target moved had a radius of 60 mm; the target itself was a round spot 14 mm in diameter moving at a constant speed of 17°/sec. The target described a complete orbit on the screen in a period of 20.5 sec. The subject had to track the target and accompany it with the mouse cursor, keeping the cursor inside the target circle.

Changes in subjects' reactivity on development of the state of monotony were tested using the unexpected appearance of an additional moving target. Thus, the main target suddenly acquired a satellite – a circle 14 mm in diameter, which moved around it at a constant speed of 25°/sec in an orbit with a radius of 70 mm (intervals between satellite appearances were random in the range 20–50 sec). When the satellite appeared, the subject had to move the cursor to it as quickly as possible and, when the cursor was within the satellite, press the mouse button. Correct pressing caused the satellite to change color to light blue to and then disappear after 0.5 sec. If the subject missed or forgot to "switch off" the satellite, it disappeared after 3 sec. After the additional target was switched off, the subject had to return the mouse cursor to the main target.

The experiment was preceded by training: over a period of 7 min, the subject was trained to perform the task without errors. The duration of the experiment was 60 min, which corresponded to 180 repeat passages of the target along the round trajectory. Errors were counted when the cursor went outside the target, when the distance between the coordinates of the mouse cursor and the coordinates of the center of the target became greater than the radius of the target, when incorrect presses were made, and when satellite appearance stimuli were missed.

During the experiment, the subject sat in a chair with a fitting for the head to reduce its range of movements, in a magnetically screened and soundproofed chamber with a low light level (18 Lx). A monitor was placed at a distance of 54–70 cm from the subject's eyes and was used for presentation of the moving target. The wrist of the working

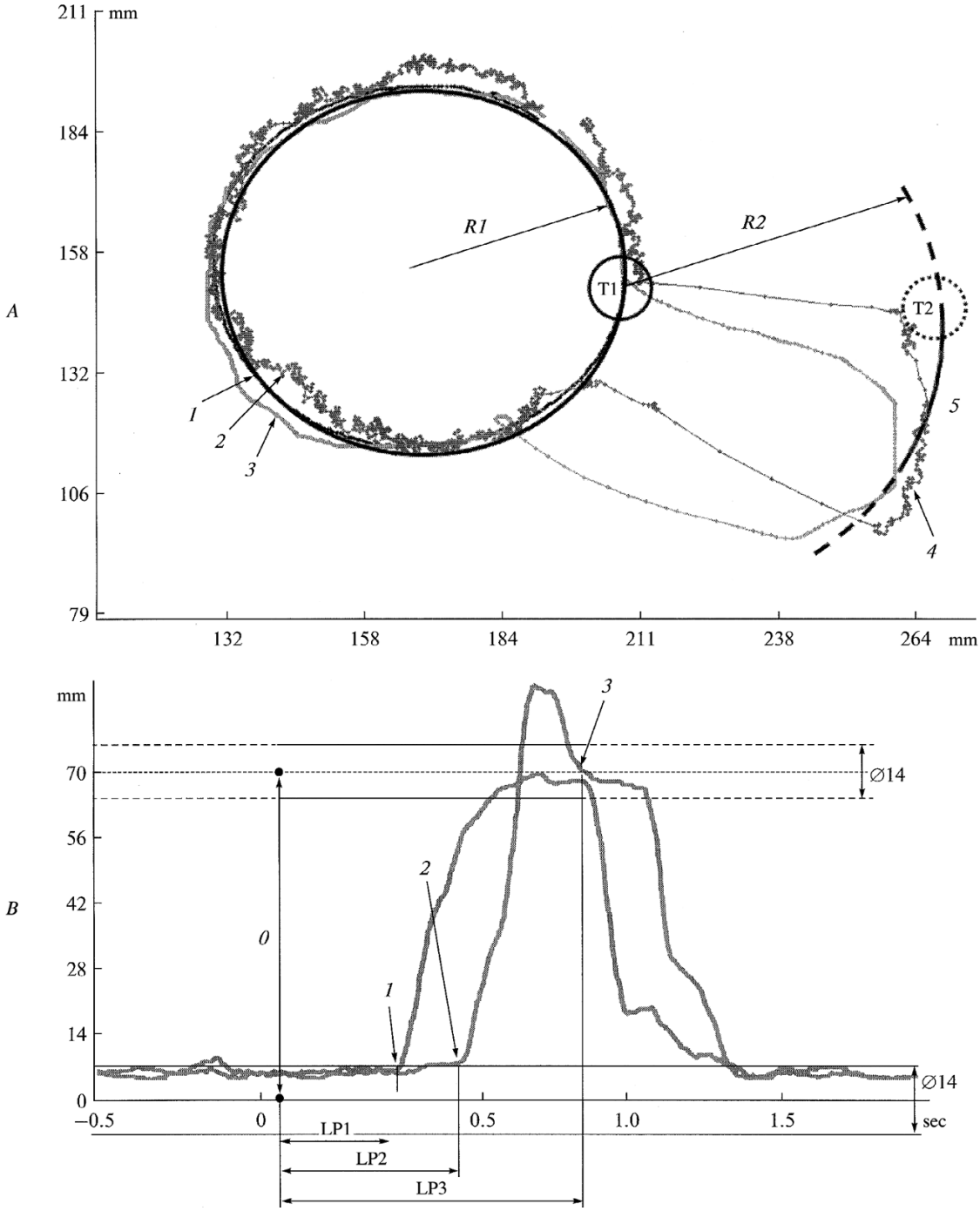

Fig. 1. Gaze and mouse cursor displacement trajectories during tracking of the main target and on appearance of the additional target. *A*: The abscissa and ordinate show distances, mm. T1 – main target; T2 – additional target. *1*) Main target movement trajectory; *2*) gaze movement trajectory; *3*) mouse cursor movement trajectory; *4*) additional target movement trajectory; *5*) the arrow shows the moment of pressing the mouse button. The continuous line shows the visible part of the trajectory of the additional target from the moment it was switched on; the dotted line shows the invisible part of the trajectory before its appearance and after its disappearance. *B*) The ordinates show the distance (mm) between the center of the main target and the coordinates of gaze (*1*) and the mouse cursor (*2*); *3*) the moment of pressing the mouse button. The "0" point on the ordinate shows the center of the trajectory of the main target; the "70" point on the ordinate shows the center of the trajectory of the additional target. Ø14 mm – horizontal lines show the boundaries of the main and additional targets; the continuous line shows the visible part of the trajectory from the moment at which the additional target was switched on; the dotted line shows the invisible part of the trajectory before its appearance and after its disappearance. *R1* is the radius of circle along with the main target moved, *R2* is the radius of the circle along which the additional target moved. The abscissa shows time, sec; the vertical arrow shows the moment the which the additional target appeared. LP1 – latent period of the onset of gaze movement; LP2 – latent period of the onset of mouse movement; LP3 – latent period of pressing the mouse button for the additional target.

hand was rested on a support beneath the monitor and was manipulated using a wireless mouse.

Task performance accuracy and reaction speeds were evaluated by recording changes in the distances between the mouse cursor coordinates and the coordinates of the centers of the main and additional targets throughout the experiment (Fig. 1, *A*).

Eye movements were also recorded throughout the experiment (Fig. 1, *A*). As the main target, moving uniformly at a low speed, was being tracked, mainly slow tracking movements of the eyes were observed. Rapid saccadic eye movements accompanying gaze displacement were seen in response to the unexpected appearance of the additional stimulus. The latent periods of saccades induced by the appearance of the satellite were measured.

The latent periods of saccades, mouse cursor movements, and mouse button presses were measured from the moment at which the satellite appeared (Fig. 1, *B*). Figure 1, *B* shows that gaze displacement started some period of time after the appearance of the additional target, followed by the onset of movement of the mouse cursor towards the new stimulus. This was followed by pressing of the mouse key and return of gaze and the mouse cursor to the main target. The latent period of saccade onset was taken as the time between stimulus delivery and displacement of gaze beyond the edges of the main target on movement towards the satellite. The latent period of onset of mouse cursor movement was taken as the time between the moment of stimulus delivery and movement of the mouse cursor outside the main target towards the satellite. The latent period of pressing the mouse button was taken as the time between stimulus delivery and pressing the mouse button when the mouse cursor was inside the satellite.

Variability in the deviation of gaze and the mouse cursor from the center of the main target was also evaluated. Thus, the mean square deviation for the distance between the center of the target and the gaze fixation point was determined during the 5-sec period before each appearance of the additional stimulus. The mean square deviation was also determined for the distances between the center of the target and the cursor location.

Eye movements were recorded using a video tracking system for contactless video recording of eye movements (Eyegaze Development System, LC Technologies, USA), based on reflection of infrared light from the cornea and allowing the coordinates of gaze direction to be identified with a time resolution of 120 Hz. The mouse cursor movement trajectory was digitized, also with a resolution of 120 Hz.

The level of arousal was assessed by recording the electroencephalogram (EEG) in leads C3 and C4, the electrooculogram (EOG), and synchronous video recordings of the subjects using a video camera with a resolution of 20–25 frames/sec. These values were recorded using a PolySon multichannel computer polygraph (Neirokom, Russia). The EEG and EOG were recorded using monopolar methods, the mean potential of two electrodes placed on the mastoid bones of the skull being used as the reference electrode. The time resolution of EEG and EOG signal recording was 200 Hz.

At the end of the experiment, after removal of artifactual segments of traces, EEG, EOG, and video recordings of subject's behavior were analyzed by three independent experts with the aim of identifying changes in the level of arousal. Sleep stages were identified using an atlas [Rentschaffen and Kales, 1968]. The experts analyzed only the EEG, EOG, and video recordings; experts did not see task performance accuracy and speed data. Synchronous EEG, EOG, and video recordings were divided into 10-sec epochs, and each epoch was assigned to one or another functional state. Overall, the whole experimental trace was divided into three states: 1) a state of calm waking – the absence of EEG and behavioral signs of falling asleep; 2) a state with a decreased level of arousal – the EEG included signs of a decreased level of arousal or somnolence, with changes in behavior pointing to a decreased level of arousal; 3) the state of microsleep – the EEG showed patterns typical of the first or even the second stages of sleep amd the subject ceased to respond to on-screen events.

Graphical presentation and visual analysis of gaze trajectories, mouse cursor movements, and mouse key pressing were performed in Matlab 7.12 and Excel 2010. Statistical analysis of study parameters, with identification of statistically significant changes in different states, was performed using Statistica 8.0. Data were normalized and compared using Student's *t* test for dependent sets.

Results

Testing on the Epworth Sleepiness Scale showed that the level of drowsiness of the subjects at the beginning of the experiment was 12.31 ± 1.26 points, which corresponded to moderate daytime drowsiness.

Expert assessments of the EEG and examination of video recordings of the subjects allowed the experiment to be divided into three states: 1) a state of calm waking; 2) a state with a decreased level of arousal; 3) a state of microsleep.

The *state of calm waking* (W) was characterized on the EEG by a clear β rhythm, periodic appearance of a low-amplitude α rhythm, and occasional θ and δ waves. Blinking was seen on the EOG.

In the *state with a decreased level of arousal* (low-arousal state, LAS), the EEG showed either a clear α rhythm or its suppression on the background of low-amplitude θ and δ waves; the β rhythm was weak. The EOG showed changes in the nature of blinking: some subjects showed an increase in blinking frequency, while others showed rarer but longer-lasting blinking. Video recordings showed defocusing of gaze. Head position and facial expression changed. Task performance was impaired: reaction time increased and occasional errors were sometimes made.

During *microsleep* (MS), the EEG showed a strong θ and/or δ rhythm, and sleep spindles were sometimes recorded. Eye closing or rolling up of the eyeballs were often seen.

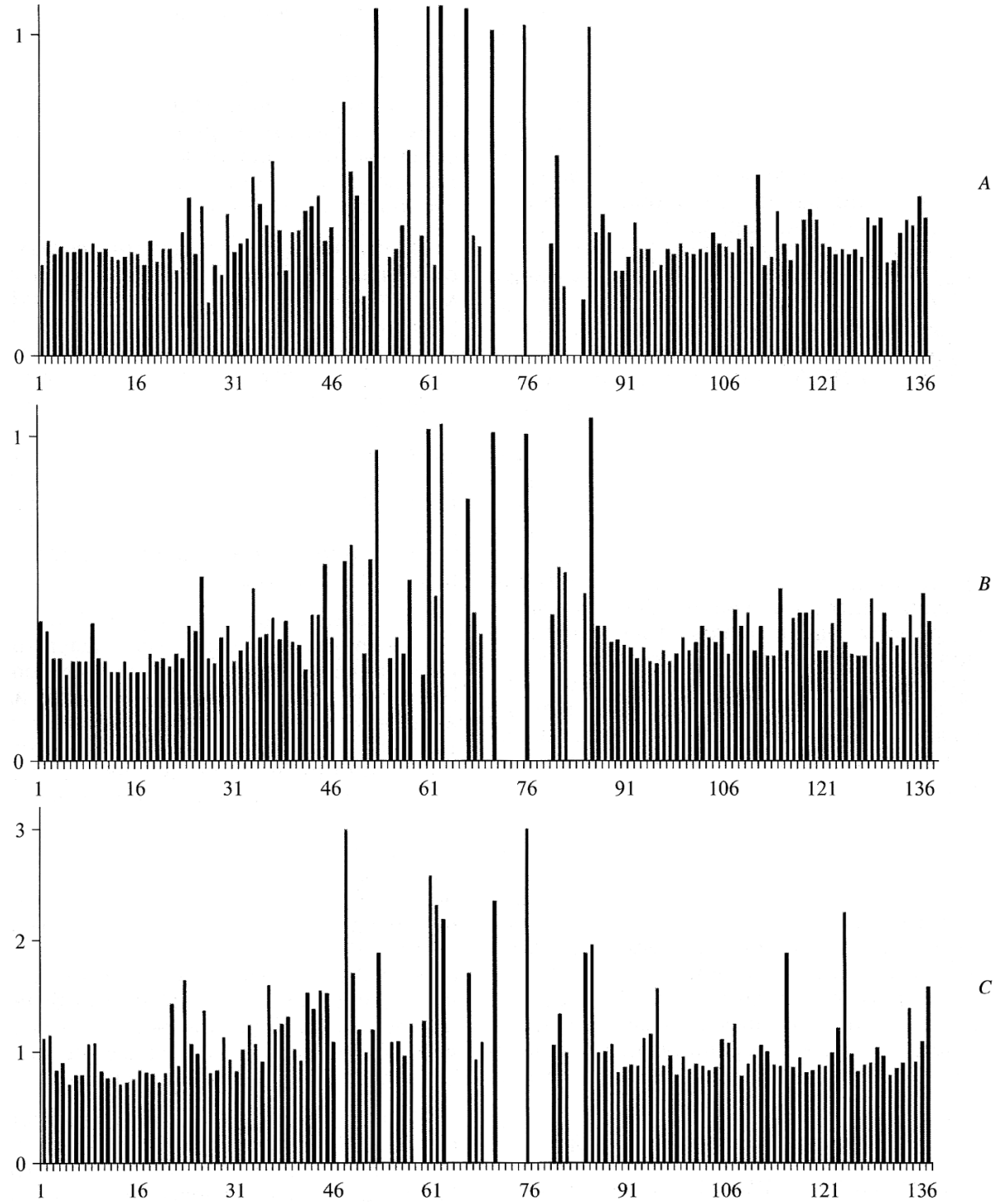

Fig. 2. Latent periods of the responses of one subject during the experiment. The abscissa shows the sequence number of each appearance of the additional target; the ordinate shows the latent periods of reactions, sec. Vertical columns show individual responses to the additional target. Areas lacking vertical columns show episodes of microsleep. *A*) Latent periods of saccades; *B*) movement of the mouse cursor; *C*) pressing of the mouse button.

When the eyes were open, the subject showed defocusing of gaze and tracking and saccadic movements were absent. As a rule, head position changed significantly (leaning towards the shoulder or falling onto the chest). The hand stopped or moved on a random trajectory. Task performance ceased during microsleep, though the subject usually woke and restarted task execution. In three cases, the subject fell asleep as previously and was woken by the experimenter after

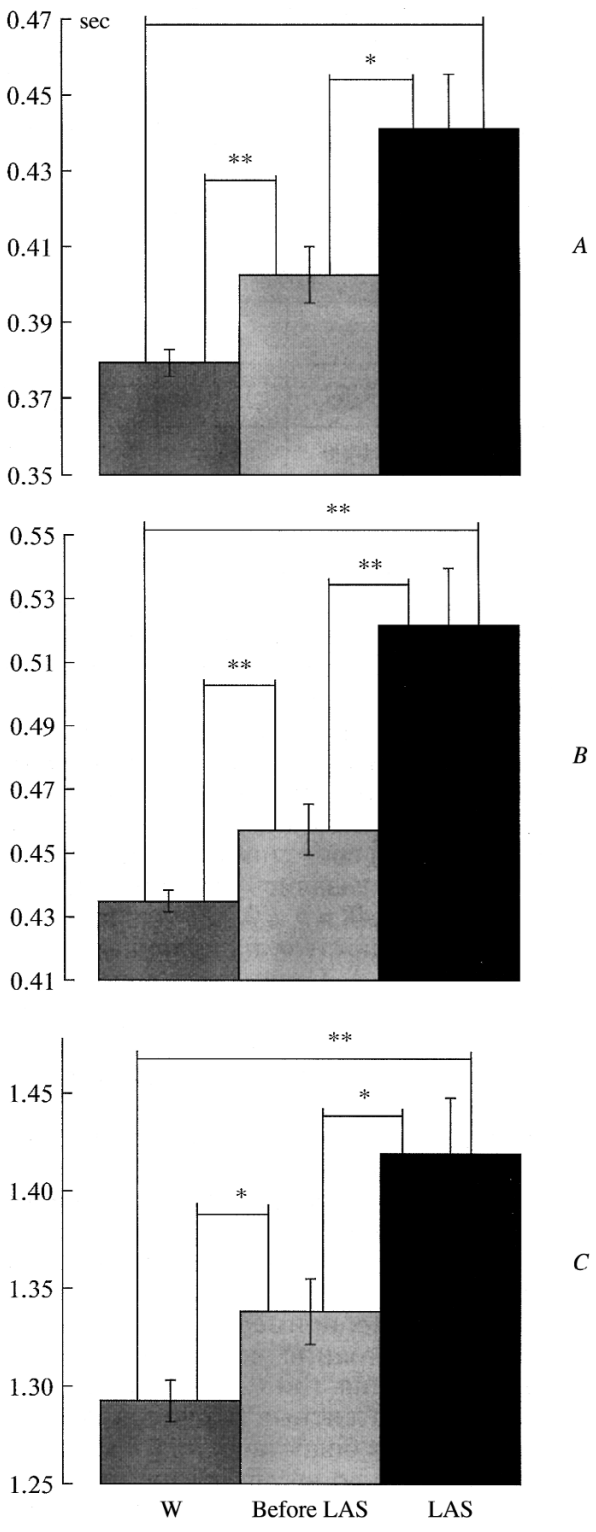

Fig. 3. Latent periods of subjects' responses in states with different levels of arousal: *A*) latent periods of gaze; *B*) latent periods of the mouse cursor; *C*) latent periods of pressing the mouse button. The ordinate shows latent periods, sec; on the abscissa: W – mean measures for state of waking; Before LAS – the state after four trials before development of the low-arousal state; LAS – low-arousal state. *Significant differences, $p < 0.05$; **$p < 0.01$ (Student's t test).

10 min. Subjects showed 5–18 episodes of microsleep during the 60-min experiment.

A total of 220 episodes displaying a reduced level of arousal were recorded in 19 subjects. In 71 of these 220 episodes, the low-arousal state was followed by microsleep, though the subject generally exited the low-arousal state to the state of calm waking without assistance. Finally, three episodes of sudden onset of microsleep were observed (two in one subject and one in a second subject).

The mean durations of all three functional states were determined. The mean duration of the stage of waking was 127 sec, with a maximum of 2460 sec and a minimum of 10 sec (or one analysis epoch). The low mean duration of the state of waking was due to a large number of short episodes of waking, positioned between states with reduced levels of arousal and episodes of microsleep (Fig. 2). The mean duration of the low-arousal state was 38 sec, with a maximum of 350 sec and a minimum of 10 sec. The mean duration of microsleep was 31 sec, with maximum of 430 sec and a minimum of 10 sec.

On average, the monotonous uniform task induced development of the low-arousal state by 20–30 min. Figure 2 shows a typical experiment. This shows that the period between additional stimulus presentations 46 to 87 showed moments when the subjects reacted to the stimulus with long delays (decreased level of arousal) or did not respond at all (microsleep). This also shows that no episodes of falling asleep occurred after the 85th stimulus.

Changes in the speeds of responses to additional stimuli were analyzed in terms of the latent periods of gaze displacement, cursor movement, and pressing of the mouse key in different functional states. We initially compared the latent periods of reactions in the low-arousal state, which was not followed by microsleep and in the low-arousal state followed by microsleep. Before microsleep, reactions were rather more delayed, though the difference between these two states of reduced arousal was not significant ($p = 0.47$, $p = 0.48$, and $p = 0.33$ for gaze, mouse cursor movement, and mouse key pressing respectively). The absence of any significant differences means that these two states could be combined for further analysis.

Figure 2 shows that some slowing of reactions in subjects could be seen 2–3 min before the moment at which the expert identified the low-arousal state. We therefore compared the latent periods of the onset of gaze movement, mouse cursor movement, and mouse key pressing on in waking, during the low-arousal state, and in response to the last four stimuli (i.e., over about 2 min) before development of the low-arousal state (Fig. 3). Significant increases in latent periods were seen before the decrease in the level of arousal, followed by increases during the low-arousal state (mean values for parameters and significance levels (p values) are shown in Table 1). Subjects' responses during the last 2 min before the development of the low-arousal state were already significantly delayed, though visual analysis

TABLE 1. Latent Periods of Subjects' Responses in States with Different Levels of Arousal

Parameter	LP of onset of gaze movement, sec			LP of onset of cursor movement, sec			LP of pressing the mouse button, sec		
State	W	Before LAS	LAS	W	Before LAS	LAS	W	Before LAS	LAS
LP	0.379 ± 0.004	0.403 ± 0.008	0.441 ± 0.014	0.435 ± 0.003	0.466 ± 0.007	0.521 ± 0.018	1.293 ± 0.010	1.338 ± 0.017	1.419 ± 0.028
p	0.003		–	0.001		–	0.014		–
	–	0.013		–	0.002		–	0.012	
	0.001	–	0.001	0.002	–	0.002	0.001	–	0.001
N	1400	572	322	1400	572	322	1400	572	322

Note. Mean values and errors of the mean ($M \pm S.E.$) are given for each state. W – the state of waking; Before LAS – the state after four trials before development of the low-arousal state; LAS – low-arousal state. *p* – Significance of differences between states; numbers on gray background have $p < 0.05$. *N* is the number of trials.

TABLE 2. Mean Square Deviations of the Distance of the Gaze and Mouse Cursor to the Center of the Target Being Tracked at Different Levels of Arousal

Parameter	Mean square deviation of gaze distance, mm		Mean square deviation of mouse distance, mm	
State	W	LAS	W	LAS
σ	3.07 ± 0.019	3.29 ± 0.049	2.21 ± 0.011	2.34 ± 0.028
p	0.013		0.010	
N	1972	322	1972	322

Note. Mean square deviations σ and errors of the mean ($M \pm S.E.$) are shown for each state. For further details see caption to Fig. 1.

of the EEG and behavior during this period of time did not permit recognition of any decrease in the level of arousal. A total of 2294 reactions to stimulus presentation were analyzed. Of these, 1400 were in the state of waking, 572 were in the state following four trials before the development of the low-arousal state, and 322 during the development of the low-arousal state.

We then analyzed how the decreased level of arousal was reflected in the accuracy of gaze and hand tracking movements on target following. Correlation analysis identified a positive relationship ($r = 0.75$, $p < 0.05$) between the mean square deviation of the distance from the center of the target to the gaze fixation point and the latent period of pressing the mouse key in response to the appearance of the additional stimulus. In other words, this may indicate that slowing of the reaction to the unexpected stimulus was preceded by less accurate following of the main target.

Comparison of mean square deviations for gaze and the mouse cursor on waking and during episodes with a reduced level of arousal (Fig. 4) demonstrated high sensitivity to the state of monotony: the decreased level of arousal produced significant increases in the variability of gaze and mouse cursor deviation from the center of the main target (means and significance levels (*p*) are given in Table 2).

Discussion

The monotonous nature of the task in our experiment produced, within 20–30 min, a low-arousal state and marked changes in in the rate and accuracy of reactions to stimuli to the level of complete cessation of work during episodes of microsleep. Subjects' EEG showed patterns typical of the first stage of sleep (the EEG "somnolence" pattern) and even the second stage of sleep. Characteristic behavioral impairments were also seen, especially at the initial stage of the decrease in the level of arousal, with an alteration in the nature of blinking, which is regarded as an early sign of increased fatigue and drowsiness [Papadelis et al., 2007; Wright et al., 2008].

The parameters analyzed here were the latent periods of gaze, mouse cursor, and mouse button pressing reactions on appearance of an unexpected stimulus – these parameters, along with mean square deviations in the distances of gaze and the mouse cursor from the center of the target being tracked, characterized the rate of the subjects' reactions – they reflected the task performance accuracy. At the moments classified by experts using EEG and behavioral changes as the low-arousal state, observations demonstrated significant increases in the latent periods of saccades, cursor movement initiation, and mouse key pressing. Target following precision also decreased – with increases in the variability of gaze and cursor deviations from the center of the target.

Correlation analysis of the study parameters identified a positive link between the latent periods of mouse key pressing in response to the appearance of the novel stimulus and the mean square deviation in the distance between the gaze and the target center 5 sec before the stimulus. In other words, slowing of the reaction as the level of arousal de-

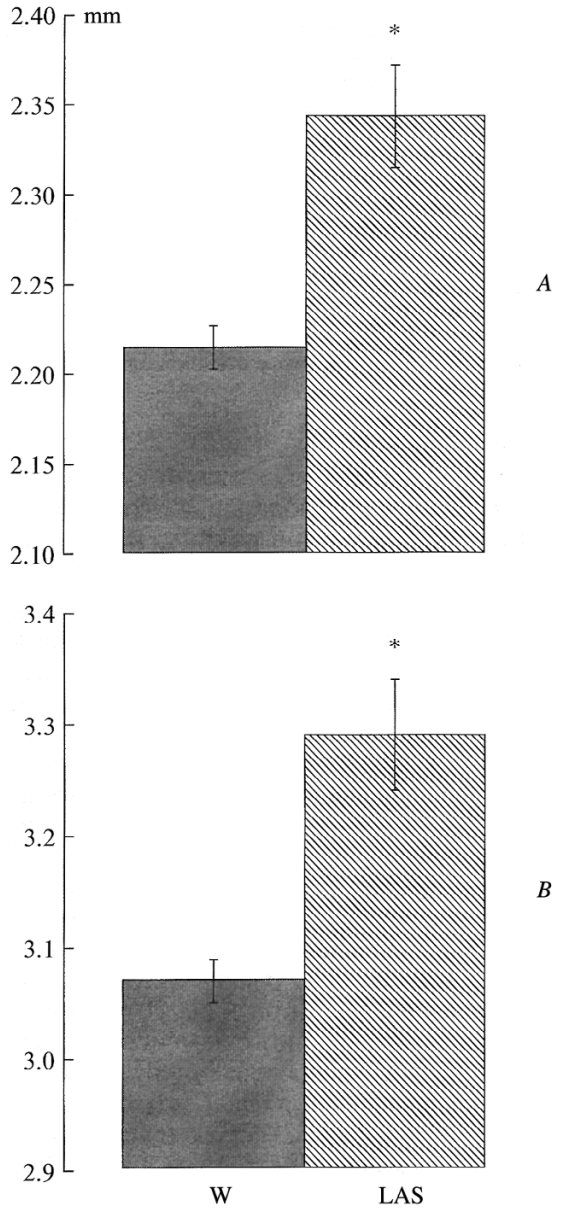

Fig. 4. Mean square deviations of the gaze and mouse cursor distances to the center of the target human being tracked in waking and in the low-arousal state: *A*) mouse cursor; *B*) gaze. The ordinate shows mean square deviation, mm; on the abscissa: W – mean values for the waking state; LAS – mean values for periods in the low-arousal state. *Significant differences, $p < 0.05$ (Student's t test).

creased occurred on the background of growth in the amplitude of gaze oscillations during target tracking. Experiments with sleep deprivation showed that an increase in the need for sleep was accompanied by an increase in reaction time and growth in the instability of behavioral reactions [Doran et al., 2001; Zhou et al., 2011]. There was no smooth change in reaction latency as the duration of waking increased and it could momentarily increase by a factor of 2–3 and then rapidly return to baseline [Boyle et al., 2008; Saper et al., 2010].

On the background of the low-arousal state, the subjects in our experiments developed episodes of microsleep. Comparison of reactions preceding these episodes with other reactions in the low-arousal state did not reveal any significant difference between them. This suggests the conclusion that microsleep can start suddenly on the background of increased drowsiness. Dementienko et al. showed that the relationship between the magnitude of the reduction in the level of arousal and the number of errors in the task was probabilistic in nature [Dementienko et al., 2008], which contradicts the intuitive concept that the transfer to sleep is gradual. It can be suggested that a high need for sleep can induce extreme short-term recruitment of the sleep mechanisms, apparent as sudden gaps in the task [Boyle et al., 2008; Saper et al., 2010].

Analysis of the latent periods of reactions to the last four stimulus presentations (i.e., over 2–3 min) before the moment at which the expert identified a decrease in the level of arousal showed that these reactions were already significantly slowed, though expert analysis of the EEG and behavior during this period of time did not allow the increase in drowsiness to be identified. Thus, the latent periods of reactions allow the development of the low-arousal state to be predicted before it is reflected in a person's activity.

Thus, analysis of the time characteristics of gaze and hand movements showed them to be highly sensitive to decreases in the level of arousal. Changes in the latent periods of hand and gaze reactions can predict the development of the low-arousal state before the point at which changes in behavior appeared and before there were any changes in the nature of blinking. The variability in gaze and cursor deviation from the center of the target was also quite sensitive to degradation of functional status.

Thus, these results lead to the conclusion that the methodology created in our laboratory provides suitable modeling of the state of monotony. We suggest that this model can be used as the basis for developing prognostic criteria for predicting the development of states with reduced levels of arousal and to take the required measures before task accuracy and safety decline. This test can also be used as a method for objective evaluation of levels of drowsiness.

Conclusions

1. At moments at which the EEG and behavioral changes were classified by experts as indicating a low-arousal state, significant increases were seen in the latent periods of saccades, the onset of mouse cursor movements, and mouse button pressing in response to the unexpected appearance of a stimulus.

2. Significant increases in the latent periods of saccades, onset of cursor movement, and pressing of the mouse button were seen 2–3 min before the moment at which the expert identified the low-arousal state.

3. The decrease in the level of arousal induced a significant increase in the variability of gaze and cursor deviations from the center of the target during tracking.

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