Brain Compensatory Mechanisms During the Prolonged Cognitive Task: fNIRS and Eye-Tracking Study

A. A. Badarin, V. M. Antipov, V. V. Grubov, A. V. Andreev, E. N. Pitsik,
S. A. Kurkin, and A. E. Hramov

***Abstract*—The problem of maintaining cognitive performance under fatigue is crucial in fields requiring high concentration and efficiency to successfully complete critical tasks. In this context, the study of compensatory mechanisms that help the brain overcome fatigue is particularly important. This research investigates the correlations between physiological, behavioral, and subjective measures while considering the impact of fatigue on the performance of working memory tasks. A combined approach of functional near-infrared spectroscopy (fNIRS) and eye-tracking was used to reconstruct brain functional networks based on fNIRS data and analyze them in terms of network characteristics such as global clustering coefficient and global efficiency. Results showed a significant increase in subjective fatigue but no significant change in performance during the experiment. The study confirmed that despite fatigue, subjects can maintain performance through compensatory mechanisms, increasing mental effort, with the level of compensation depending on the task's complexity. Furthermore, the study showed that compensatory effort maintains the efficiency of the frontoparietal network, and the degree of compensatory effort is related to the difference in response times between high- and low-complexity tasks.**

***Index Terms*—Adaptive mechanism, brain functional networks, compensatory effort, eye tracker, functional near-infrared spectroscopy (fNIRS), mental fatigue, network measures.**

I. INTRODUCTION

In recent years, the fast-paced lifestyle and the constant influx of information have led to an increase in the duration of tasks that require prolonged periods of intense concentration and mental activity. The brain's adaptation to such tasks plays a crucial role that needs to be understood from both fundamental and applied perspectives. It is widely known that the brain network is capable of adapting to changing environmental conditions not only through changes in its structure [1], but also through changes in the brain's functional network [2], [3], [4].

This adaptivity of the brain is mainly ensured by its modular structure, which allows the brain to dynamically switch between the states of separated and integrated information processing [5], [6]. The switching of brain modes between segregation and integration is the key to cognitive adaptation and combating fatigue. Segregation allows specialized processing in individual brain areas, while integration facilitates communication between different areas. This dynamic balance supports the brain's ability to allocate resources efficiently, adapt to task demands, and reduce cognitive fatigue by optimizing patterns of functional connectivity [7].

Thus, fatigue plays a critical role in brain adaptation mechanisms and serves as a physiological indicator that the body and brain require restful recovery to safeguard against damage caused by excessive strain. Unfortunately, in many everyday situations, we often need to suppress this system to compensate for the decrease in performance resulting from fatigue.

Compensatory effort, in the context of fatigue, refers to strategies or actions taken to overcome or alleviate the effects of fatigue. For instance, a study by Hockey with coauthors [8] considers compensatory effort in the context of regulating human performance under stress and high workload. The proposed model of compensatory control suggests that performance can be maintained under stress and fatigue by engaging additional resources but at the expense of increased subjective effort and behavioral and physiological costs.

The study by Nakagawa et al. [9] aimed to isolate the impact of compensatory effort on neurovascular demand using functional magnetic resonance imaging during a visual–auditory divided attention task. The findings revealed that compensatory effort was more activated in complex tasks compared to simple ones following exposure to fatigue.

Compensatory brain activity was investigated in the context of long-term continuous performance of a cognitive control task [10]. The authors found that anterior frontal brain activity is recruited to compensate for fatigue-induced impairments in the primary network associated with task performance.

Although numerous studies exist, the mechanisms underlying compensatory brain activity remain largely elusive.

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The authors are with Immanuel Kant Baltic Federal University, Kaliningrad 236041, Russia (e-mail: Badarin.a.a@mail.ru).

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Specifically, the impact of compensatory mechanisms on memory has yet to be thoroughly investigated. In our study, we employed a working memory task derived from the Sternberg paradigm, which participants engaged in over an extended period. It is important to note that the Sternberg working memory test is primarily focused on examining verbal working memory, specifically the phonological loop [11]. Additionally, the simultaneous presentation of multiple characters on the screen may engage the visuospatial sketchpad. Therefore, the test is effectively designed to evaluate the central executive system's overall capability to manage information and tasks within working memory. Consequently, the Sternberg Working Memory Test enables a comprehensive assessment of working memory performance, making it, in our view, particularly suitable for examining the influence of mental fatigue and compensatory efforts in this domain. Note that working memory is a significant component of higher cognitive functions, including attention control and nonverbal thinking [12], [13], [14].

This study aims to explore the mechanisms of brain compensation in response to mental fatigue and their impact on cognitive performance and working memory. In the applied field, understanding the brain's compensatory mechanisms during prolonged cognitive tasks could lead to the development of methods and techniques that can mitigate mental fatigue and improve cognitive performance in various settings such as education, healthcare, and others [15].

To comprehensively study the mechanisms of compensation, we monitored participants' multimodal data during the experiment. We recorded the brain's hemodynamics using functional near-infrared spectroscopy (fNIRS), eye movements using an eye-tracking device, and subjective and behavioral characteristics.

It should be noted that eye tracking provides information about gaze direction and the duration of fixation on specific stimuli, which can reveal critical aspects of visual attention and perception [16], [17]. On the other hand, fNIRS reflects changes in cerebral blood flow and oxygenation level, which are indicators of neural activity in specific brain regions. By combining these two techniques, we can study how neural activity in certain brain regions relates to visual attention and perception during cognitive tasks. This can provide insight into the neural mechanisms underlying these processes. Additionally, the simultaneous use of eye tracking and fNIRS is a powerful tool for investigating cognitive processes and can provide new insights into the relationship between neural activity and behavior.

II. MATERIALS AND METHODS

A. Participants

Fourteen healthy subjects (9 males and 5 females) aged from 18 to 22 with normal or corrected-to-normal visual acuity participated in the experiments. All of them provided written informed consent in advance. All participants were informed about the experimental task, had the opportunity to ask any related questions, and received appropriate answers. The experimental studies were performed in accordance with the Declaration of Helsinki and approved by the local Research Ethics Committee of Innopolis University.

B. Subjective Tests

We used the Multidimensional Fatigue Inventory (MFI-20) for comprehensive subjective fatigue assessment [18]. It is a 20-item self-report that assesses fatigue on five scales: General Fatigue, Physical Fatigue, Mental Fatigue, Reduced Motivation, and Reduced Activity. The test contains a number of statements. A participant needs to choose the number from the set 1, 2, 3, 4, 5, where "1" is "Yes, that's true" and "5" is "No, that's not true" for each of the statements presented.

We used the Raw NASA task load index (Raw NASA-TLX) to estimate the load induced by the experimental task [19], [20]. This test provides an assessment of the following factors: Mental, Physical, and Temporal Demands, Frustration, Effort, and Performance. Note, that Raw NASA-TLX is a modification of NASA-TLX which eliminates the weighting process of the results altogether.

We used the visual analog scale (VAS) to assess subjective fatigue during solving the experimental task [21], [22]. VAS is a quick test aimed at visual subjective assessment of fatigue. The test goes as follows: "Degree of Fatigue" scale with a slider and the labels "Low" and "High" are shown on a screen, a subject needs to move the slider with the mouse so that it reflects the current degree of fatigue on the scale.

C. Experimental Task

We used the Sternberg Working Memory Task as the main experimental task [23], [24], [25], [26]. In the Sternberg Working Memory Task, the subject is presented with a set of letters and is required to remember them. Later, they are presented with a single letter and must determine whether that letter was part of the original set. To ensure that the subject remembers a semantic meaning of the letter, rather than its visual image, the letter is presented in lowercase. Fig. 1(a) illustrates the implementation of our experimental tasks. Each task began with a black screen on which a white cross was shown for 1.5–2.5 s, to attract the subject's attention. Then, a stimulus appeared in the form of a set of 7 symbols, in which 2–7 symbols were represented with capital Cyrillic letters, and the others were represented by an asterisk (*). The set of letters was presented for 1.5–2.5 s, and the subject was asked to remember all the letters shown. A black screen was shown again for 3–7 s, after which a lowercase letter was presented. The subject was then required to decide whether the letter was in the set or not and provide an answer. The time interval for the answer was 4 s, which included 2 s of letter presentation and the following 2 s of black screen.

D. Experimental Procedure

We demonstrated the task on a screen of 24" monitor (52.1 × 29.3 cm) with the 1920 × 1080 pixels resolution and 60 Hz refresh rate [Fig. 1(c)]. The distance between the subject's eyes and the monitor was approximately $\sim$0.8 m, and a visual angle was approximately $\sim$0.37 rad.

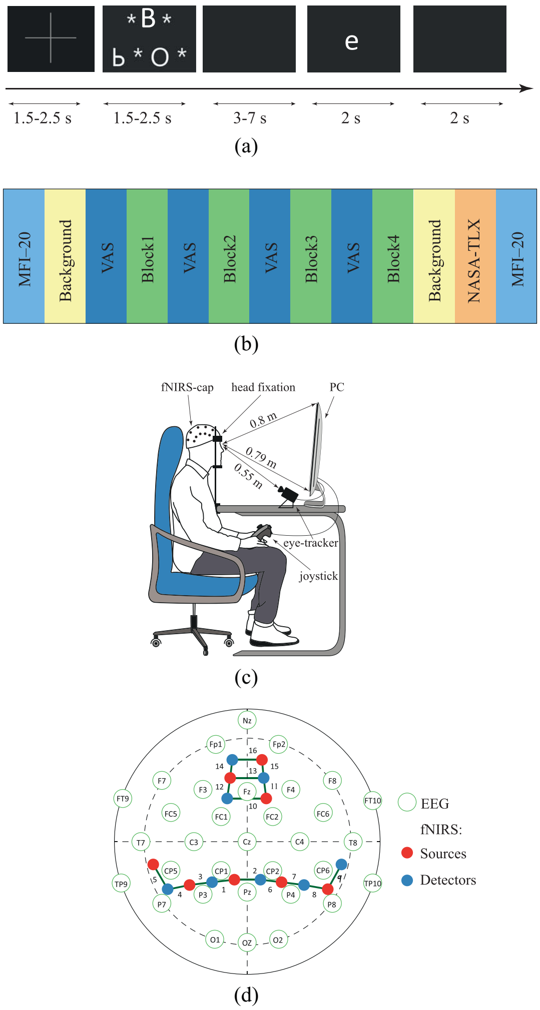


Fig. 1. (a) Scheme of one task from the block of the main part: cross for the fixation of attention, presentation of a set of letters, pause, test, pause for a response. (b) The general design of the experiment. (c) Schematic representation of the experimental setup. (d) Scheme of the fNIRS optodes arrangement used in the study. The standard positions of EEG channels are provided to better understand the arrangement of the fNIRS channels.

During the experiment, the subject sat in the "CE-1" chair (Neurobotics, Russia) specifically designed for neurophysiological experiments. The monitor for stimulus presentation was placed on the table in front of the subject's eyes, and we used a joystick to register responses to stimuli [see Fig. 1(c)].

At the beginning of the experiment, we comprehensively estimated the subject's baseline level of fatigue using the MFI-20 test. Then, the subject performed the main part of the experiment. After the main part, we estimated the task-induced workload on the subject using the Raw NASA-TLX and fatigue using the MFI-20.

The main part of the experiment consists of four identical blocks [Blocks 1–4 in Fig. 1(b)]. Each block consists of 72 tasks (see Experimental task section): 12 repetitions for each number of letters (from 2 to 7) in the presented set. Among the 12 repetitions, 6 tasks contain the target letter, and 6 do not. The order in which the tasks were presented was randomized for each subject. Before and after each block, we estimated the current level of fatigue using VAS.

We divided the tasks into two levels of complexity: Low complexity (2 to 3 letters) and High complexity (6 to 7 letters). We analyzed the performance and response time depending on the level of complexity. Here, performance is defined as the proportion of correct answers, and response time is the average time elapsed from the presentation of the test letter to the answer. Note that we used only correct responses for calculating the response time. We also analyzed the difference between the response times (DRT) for High and Low complexity tasks.

The entire experiment lasted approximately 70 min for each participant, including short recordings of the eyes-open resting state (60 s) before and after the main part f the experiment.

E. fNIRS Analysis

We recorded hemodynamic signals using the NIRScout device manufactured by NIRx Company (Germany). The NIRScout system has a resolution of 7.8125 Hz and consists of eight sources and eight detectors placed on the subject's scalp in the frontal and parietal cortices, as shown in Fig. 1(d). Each "source-detector" pair was placed about 3 cm close to each other to form an fNIRS channel. In this experiment, we utilized 16 fNIRS channels. Channels 1–9 cover the Parietal Lobe, including the Somatosensory Association Cortex, Supramarginal, and Angular gyri, and marginally involve the Middle Temporal Gyrus. Channels 10–16 cover the Granular Frontal Gyrus (Dorsolateral Prefrontal Cortex, DLPFC) and the Intermediate Frontal Gyrus (includes the Frontal Eye Fields). For the alignment of channels with these brain regions, the Brainnetome Atlas (https://atlas.brainnetome.org/) was employed.

Such choice of optode placement is motivated by the reliable findings indicating that the fronto-parietal network plays a critical role in working memory and cognitive control [27], [28], [29], [30]. Additionally, recent research has demonstrated the involvement of the frontal lobe in compensatory mechanisms [10].

We used specialized NIRx software to perform the fNIRS data acquisition and preprocessing procedure. It is well-known that experimental fNIRS data are affected by side physiological noises and artifacts such as Mayer wave ($\sim$0.1 Hz), respiration ($\sim$0.25 Hz), and heartbeat ($\sim$1 Hz). We applied the $0.04-0.07$ Hz band-pass filter to the fNIRS signals to remove physiological noises and select the frequency range of interest. Note, that this range lies within the range of frequencies often analyzed in the functional brain connectivity studies [31], [32]. After filtering the raw fNIRS data, we calculated changes in the level of total hemoglobin (totHb) concentration using a modified Beer–Lambert law [33]. We believe that employing totHb as a marker provides a comprehensive representation of cerebral blood volume fluctuations, indicative of neuronal activity during cognitive tasks, as it encompasses alterations in both oxyHb and deoxyHb levels. To determine brain functional connectivity, we calculated the Pearson correlation coefficients r_{ij} (i and j are channel numbers) for each pair of totHb signals in each block separately. We then averaged the correlation coefficients in the frontal (r_F) and parietal (r_P) areas, as well as between them (r_{FP})

$$r_F = \frac{1}{N_F} \sum_{i,j \in [10,16]; i<j} r_{i,j} \tag{1}$$

$$r_P = \frac{1}{N_P} \sum_{i,j \in [1,9]; i<j} r_{i,j} \tag{2}$$

$$r_{FP} = \frac{1}{N_{FP}} \sum_{i \in [1,9], j \in [10,16]} r_{i,j}. \tag{3}$$

Here, i and j denote the indices corresponding to channel numbers. The parameters $N_F = 21$, $N_P = 36$, and $N_{FP} = 63$ quantify the counts of correlation coefficients internally within the Frontal region, within the Parietal region, and interregionally between the Frontal and Parietal regions, respectively.

To characterize changes in the frontoparietal network during the experiment, we calculated network measures of functional integration and segregation, such as global efficiency and global clustering coefficient, respectively. These calculations derived from an analysis of the correlation matrix, which encapsulates the interactions across all channels, explicitly manifested as a 16×16 matrix. We used the Brain Connectivity Toolbox for Matlab to calculate these measures [34].

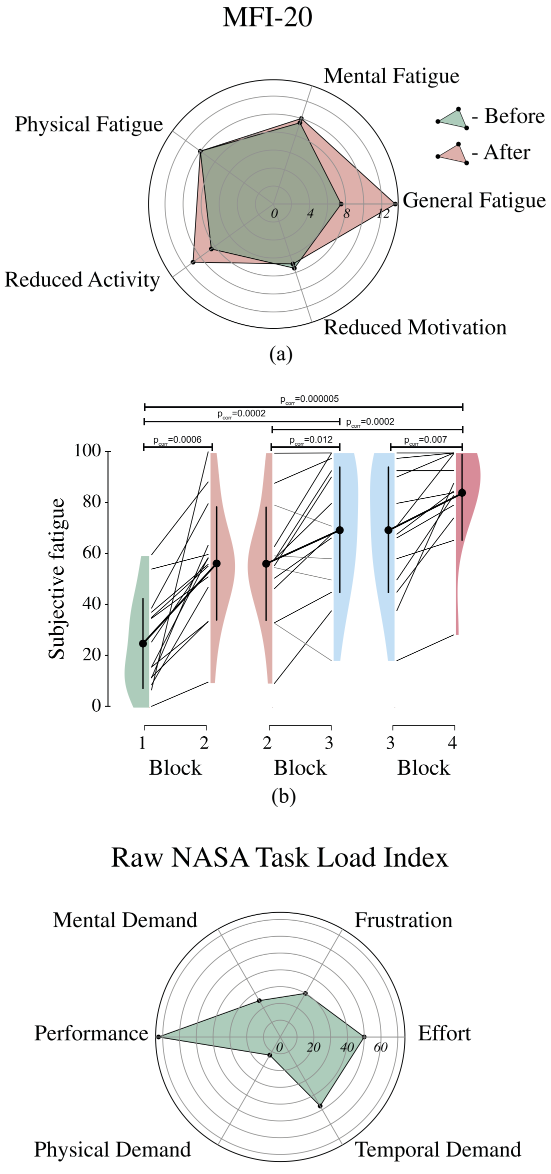
It is important to note that segregation in a brain network reflects its ability for specialized information processing, and the presence of clusters in functional networks indicates segregation of neural processing. Integration in a brain network, on the other hand, reflects its ability to quickly combine specialized information from different brain regions. Integration measures are designed to characterize this property by assessing the complexity of information exchange between brain regions. For more information about these network measures, please refer to [34].

F. Eye Tracker Data Analysis

We used the EyeLink 1000 Plus (Canada), which is one of the most popular and accurate eye trackers for scientific studies, to track the point of gaze at a frequency of 1000 Hz. For the detection of fixations, we used the velocity-based algorithm proposed in the Ref. [35] with the parameter $\lambda = 15$ and a moving average smoothing with a window size of 3. The parameter λ specifies which multiple of the standard deviation of the velocity distribution should be used as the detection threshold. Additionally, we set the minimum fixation duration threshold to 40 ms.

In our analysis, we used block-averaged fixation duration and considered the proportion of medium fixations to the total number of fixations. Here, medium fixations refer to fixations with durations in the range of 150–900 ms. According to previous studies, medium fixations are associated with cognitive information processing and reflect high-level cognitive processes [36].

Another characteristic we used in our study is the dynamics of block-averaged pupil size during the experiment. To minimize between-subject variability, we considered the normalized pupil size (NPS) by comparing the pupil size (PS) at all blocks to the one averaged during 60 s before the main part of the experiment ($\mathrm{PS}_{\mathrm{baseline}}$): $\mathrm{NPS} = (\mathrm{PS} - \mathrm{PS}_{\mathrm{baseline}})/\mathrm{PS}_{\mathrm{baseline}}$



(a)

(b)

(c)

Fig. 2. Results of subjective questionnaire: (a) median values of MFI-20 before and after task solving; (b) results of VAS during the task. Here, p_{corr} is Bonferroni-corrected statistical level on the multiple comparisons in posthoc analysis; (c) median values of Raw NASA TLX.

G. Statistical Analysis

The main effects at the group-level were evaluated via repeated-measures ANOVA and effect size was estimated using partial eta-squared (η_n^2). The post hoc analysis used either paired samples t-test and effect size was estimated using Hedges' g. The Wilcoxon signed-rank test was employed to evaluate changes in fatigue induced by an experimental task, as measured by the multidimensional questionnaire MFI-20 and effect size was estimated using Rank–Biserial Correlation (RBC). Normality was tested via the Shapiro–Wilk test.

TABLE I
ANOVA SUMMARY

Dependent Variables	Factors	dF1	dF2	F	p	η_p^2
Subjective fatigue	Block	3	39	36.87	< 0.000001*	0.71
Response time	Block	3	39	2.32	0.09	0.15
	Complexity	1	13	38.78	0.000031*	0.74
	Block * Complexity	3	39	4.09	0.0129*	0.239
Performance	Block	3	39	0.64	0.6	0.046
	Complexity	1	13	26.62	0.00018*	0.67
	Block * Complexity	3	39	2.23	0.1	0.146
DRT	Block	3	39	4.087	0.00129*	0.239
Duration of fixations	Block	3	39	9.8	0.00006*	0.43
Proportion of medium fixations	Block	3	39	7.82	0.0003*	0.376
Pupil size	Block	3	39	4.31	0.01*	0.249
Clustering coefficient	Block	3	39	4.78	0.006*	0.269
Efficiency	Block	3	39	4.98	0.005*	0.277
Frontal	Block	3	39	1.68	0.19	0.114
Parietal	Block	3	39	5.66	0.003*	0.304
Frontal–Parietal	Block	3	39	3.62	0.021*	0.218

Note: Here, "*" indicates the level of significance $p < 0.05$.

The group-level correlation analysis between all pairs of characteristic changes during the experiment was performed using repeated measures correlation [37]. We also used Spearman correlation to search for a relationship between MFI-20 and behavioral results. We apply Spearman's correlation analysis because it demonstrates insensitivity to the normality of data distribution and provides a more adequate approach for investigating relationships between continuous and discrete variables. The significance threshold for correlation was set at $p < 0.05$. We used several open-source statistical packages in Python, such as Pingouin, SciPy and Statsmodels for statistical analysis.

III. RESULTS

A. Subjective Level

The results associated with the subjective questionnaire are shown in Fig. 2. The MFI-20 results demonstrated an increase in the general fatigue level after performing the task [see Fig. 2(a)]. We conducted a statistical assessment of the changes in fatigue levels across all test scales, as well as the overall score. We found that both general fatigue ($p_{\text{corr}} = 0.0087$, rank-biserial correlation $(RBC) = 1$; the p_{corr} values were adjusted using the Bonferroni method to account for multiple comparisons, with six comparisons made for each scale and the total score) and the total score ($p_{\text{corr}} = 0.0051$, $RBC = 0.92$) manifested statistically significant increases. The median value of general fatigue increased from 8 to 14. It is worth noting that before starting the task performance, the participants had low values (less than 8 out of the maximum possible 20) across all scales of MFI-20, which confirms that none of the subjects had any type of asthenia. Additionally, subjective fatigue increased significantly during the experiment [see Tables I, II and Fig. 2(b)]. According to Raw NASA TLX, we found that task performance made the main contribution to increasing fatigue [see Fig. 2(c)].

B. Behavioral Data

The main results of performing the task are shown in Fig. 3. All subjects accomplished the task successfully. We found that performance and response time depended on the complexity of the task: the performance on the high complexity was lower than on the low complexity, and the response time on the high complexity was higher than on the low complexity. At the same time, we did not find significant changes in performance or response time during the experiment. However, we found a decrease in the difference between the responses for the high and low complexities during the experiment (see Tables I and III).

C. Fixations and Pupil Size

The main results on the gaze fixations and pupil size are shown in Fig. 4. We found that the duration of fixations, the proportion of medium fixations, and the normalized pupil size decreased during the task. The strongest changes are observed for the duration of fixations. It is clearly seen that significant changes are observed between all blocks of the experiment with the exception of the difference between the first and second blocks [see Fig. 4(a)]. The decrease in the proportion of medium fixations is less pronounced and the significant change is observed only between the first and fourth blocks [see Fig. 4(b)]. We did not find significant changes in the normalized pupil size in post hoc analysis. However, for the uncorrected statistical level, we revealed the significant differences between the first and all the other blocks [see Fig. 4(c)].

D. Connectivity Analysis

We found a significant decrease in functional connectivity within the parietal area and between the frontal and parietal areas during the task execution [see Fig. 5(a) and 5(b)]. Significant decreases in connectivity within the parietal area are observed between the first and fourth blocks and the first and third blocks. At the same time, the connectivity between frontal and parietal areas had differences only between the first and fourth blocks. We did not find significant changes within the frontal area. Also, we analyzed the cortical frontoparietal network from the point of view of network measures such as the global clustering coefficient and global efficiency. We found that these measures also significantly decrease during task execution [see Fig. 5(c) and 5(d)]. In post hoc analysis, we found

TABLE II
POSTHOC ANALYSIS

Dependent Variables	Compared Blocks	T-Value	Degrees of Freedom	p_{unc}	p_{corr}	Effect Size (Hedge's g)
Subjective fatigue	1 versus 2	−5.261053	13	0.000154	0.000616*	−1.468649
	1 versus 3	−5.956028	13	0.000048	0.000239*	−1.959949
	1 versus 4	−8.719419	13	0.000001	0.000005*	−3.060101
	2 versus 3	−2.908371	13	0.012210	0.012210*	−0.533521
	2 versus 4	−4.913828	13	0.000283	0.000849*	−1.273767
	3 versus 4	−3.577785	13	0.003372	0.006744*	−0.624191
DRT	1 versus 2	2.588734	13	0.022481	0.134888	0.497464
	1 versus 3	1.330402	13	0.206253	0.412507	0.231401
	1 versus 4	2.445330	13	0.029470	0.147352	0.722435
	2 versus 3	−1.700380	13	0.112843	0.338529	−0.325397
	2 versus 4	0.961960	13	0.353622	0.412507	0.255209
	3 versus 4	2.151659	13	0.050802	0.203209	0.586724
Duration of fixations	1 versus 2	1.469414	13	0.165502	0.165502	0.197448
	1 versus 3	2.916130	13	0.012030	0.039279*	0.517327
	1 versus 4	3.935830	13	0.001707	0.010240*	0.836760
	2 versus 3	2.555469	13	0.023944	0.047887*	0.276594
	2 versus 4	3.351009	13	0.005211	0.026053*	0.569277
	3 versus 4	3.021736	13	0.009820	0.039279*	0.346358
Proportion of medium fixations	1 versus 2	2.878203	13	0.012938	0.064690	0.564703
	1 versus 3	2.737126	13	0.016950	0.067798	0.620858
	1 versus 4	3.400876	13	0.004734	0.028406*	0.928840
	2 versus 3	0.767862	13	0.456291	0.456291	0.101941
	2 versus 4	2.416954	13	0.031082	0.093246	0.463259
	3 versus 4	2.339636	13	0.035913	0.093246	0.355430
Pupil size	1 versus 2	2.289096	13	0.039449	0.202150	0.622492
	1 versus 3	2.217826	13	0.044998	0.202150	0.733637
	1 versus 4	2.373868	13	0.033692	0.202150	0.825469
	2 versus 3	0.838456	13	0.416926	0.698807	0.167926
	2 versus 4	1.440879	13	0.173269	0.519807	0.288301
	3 versus 4	0.970719	13	0.349404	0.698807	0.119670
Clustering coefficient	1 versus 2	2.139588	13	0.051934	0.207735	0.281190
	1 versus 3	2.506270	13	0.026276	0.131381	0.388114
	1 versus 4	3.265378	13	0.006144	0.036862*	0.576026
	2 versus 3	0.796838	13	0.439856	0.439856	0.131407
	2 versus 4	1.745098	13	0.104544	0.313632	0.320263
	3 versus 4	1.524977	13	0.151218	0.313632	0.176823
Efficiency	1 versus 2	2.097232	13	0.056094	0.224375	0.249489
	1 versus 3	2.708826	13	0.017890	0.089451	0.387828
	1 versus 4	3.063632	13	0.009059	0.054355	0.530721
	2 versus 3	0.945543	13	0.361626	0.361626	0.137862
	2 versus 4	1.764610	13	0.101096	0.303287	0.298454
	3 versus 4	1.436075	13	0.174606	0.349212	0.170848
Pariental	1 versus 2	2.761349	13	0.016183	0.064732	0.429207
	1 versus 3	3.106488	13	0.008342	0.041710*	0.545735
	1 versus 4	3.402154	13	0.004723	0.028336*	0.776507
	2 versus 3	0.578578	13	0.572762	0.572762	0.101123
	2 versus 4	1.440272	13	0.173437	0.346875	0.357801
	3 versus 4	1.730086	13	0.107268	0.321803	0.269728
Frontal-Pariental	1 versus 2	1.755282	13	0.102731	0.444542	0.217018
	1 versus 3	1.838696	13	0.088908	0.444542	0.317575
	1 versus 4	2.728432	13	0.017233	0.103400	0.468080
	2 versus 3	0.706147	13	0.492558	0.492558	0.103935
	2 versus 4	1.743638	13	0.104806	0.444542	0.261196
	3 versus 4	1.446355	13	0.171755	0.444542	0.158329

Note: Here, "*" indicates the level of significance $p < 0.05$.

significant changes in the global clustering coefficient of the cortical network between the first and fourth blocks. However, we did not find significant changes in the global efficiency of the cortical network.

E. Correlation Analysis

We analyzed correlations among all pairs of characteristics that vary during task execution [see Fig. 6(a)]. Our investigation revealed a multitude of significant correlations.

Primarily, subjective fatigue was found to correlate with most of the characteristics evaluated. Specifically, it shows a positive correlation with the response time for tasks of low complexity ($r = 0.5$, $p = 0.0007$) and a negative correlation with both the duration of fixations ($r = -0.61$, $p = 0.00002$) and connectivity within the parietal area ($r = -0.47$, $p = 0.002$). Interestingly, no correlation was observed between subjective fatigue and connectivity within the frontal area.

Moreover, our findings indicate a positive correlation between the difference in average response times for high- and

TABLE III
POSTHOC ANALYSIS

Dependent Variables	Complexity	Compared Blocks	T-Value	Degrees of Freedom	p_{unc}	p_{corr}	Effect Size (Hedge's g)
Response	High	1 versus 2	0.532537	13	0.603338	1.000000	0.074859
	High	1 versus 3	−0.553705	13	0.589178	1.000000	−0.103551
	High	1 versus 4	−0.395660	13	0.698772	1.000000	−0.088797
	High	2 versus 3	−1.467584	13	0.165991	1.000000	−0.191083
	High	2 versus 4	−0.981381	13	0.344317	1.000000	−0.178455
	High	3 versus 4	0.124629	13	0.902724	1.000000	0.019795
	Low	1 versus 2	−2.992098	13	0.010396	0.114352	−0.316685
	Low	1 versus 3	−1.863394	13	0.085149	0.681192	−0.344178
	Low	1 versus 4	−4.243950	13	0.000958	0.011495*	−0.678608
	Low	2 versus 3	−0.106937	13	0.916472	1.000000	−0.017638
	Low	2 versus 4	−2.779506	13	0.015631	0.156308	−0.390804
	Low	3 versus 4	−2.542725	13	0.024528	0.220750	−0.383777

Note: Here, "*" indicates the level of significance $p < 0.05$.

low-complexity tasks and several metrics: duration of fixations ($r = 0.36$, $p = 0.025$), global efficiency ($r = 0.44$, $p = 0.004$), global clustering coefficient ($r = 0.37$, $p = 0.014$), connectivity within the parietal area ($r = 0.41$, $p = 0.006$), and connectivity between the frontal and parietal areas ($r = 0.33$, $p = 0.033$).

Additionally, response times on low-complexity tasks were found to negatively correlate with most features measured by eye-tracking and functional near-infrared spectroscopy (fNIRS), with the sole exception of connectivity within the frontal area. In contrast, performance on high-complexity tasks positively correlates with connectivity within the frontal area ($r = 0.38$, $p = 0.012$), and between the frontal and parietal areas ($r = 0.37$, $p = 0.013$).

Furthermore, characteristics of gaze fixations were positively correlated with efficiency, the clustering coefficient, connectivity within the parietal area, and connectivity between the frontal and parietal areas.

Finally, we analyzed correlations between behavioral characteristics and average values of the MFI-20 questionnaire [see Fig. 6(b) and 6(c)]. We revealed that the difference between the average response times for high and low complexities correlates negatively with mental fatigue value ($\rho = -0.73$, $p = 0.003$) and the score of MFI-20 ($\rho = -0.72$, $p = 0.004$). The response time for high complexity correlates negatively with general fatigue ($\rho = -0.68$, $p = 0.008$) and the score of MFI-20 ($\rho = -0.77$, $p = 0.001$).

IV. DISCUSSION

In this article, we analyzed the dynamics of physiological, behavioral, and subjective metrics during a prolonged working memory task. We focused on the effect of fatigue on task performance. We found that our task caused a significant increase in subjective fatigue. However, it did not cause a significant change in task accuracy. At the same time, the increase in fatigue was accompanied by an increase in reaction time only for low complexity tasks, while the reaction time for high complexity tasks remained unchanged throughout the experiment.

We also found that the increase in fatigue was associated with a decrease in frontoparietal network efficiency, global clustering coefficient, and connectivity strength within the parietal lobe and between the frontal and parietal regions. Note that connectivity within the frontal region did not change over the course of the experiment and did not correlate with subjective fatigue. We also found that the increase in fatigue was accompanied by a decrease in the duration of fixations, the proportion of medium fixations, and pupil size.

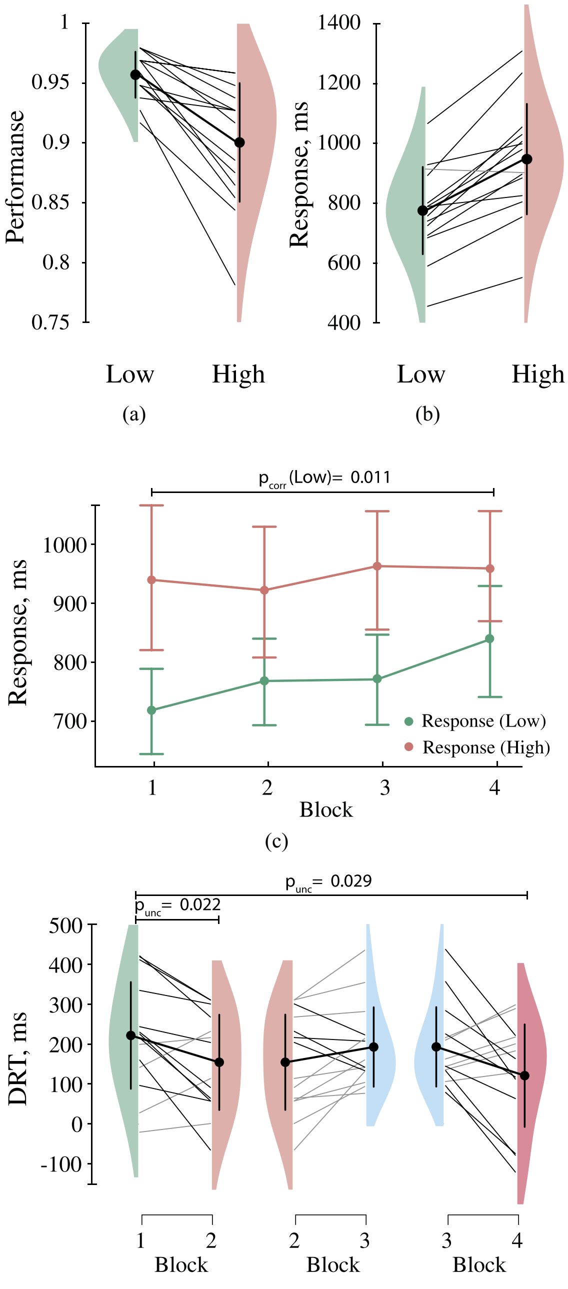
Correlation analysis detected characteristics of the frontoparietal network associated with prolonged execution of the working memory task. We found that connectivity within the frontal area, and between the frontal and parietal areas, was associated with accuracy in solving high complexity tasks. Moreover, higher accuracy was characterized by higher connectivity in these areas. Response times for low complexity tasks correlated with the same frontoparietal network indices and oculomotor characteristics and in the same direction as subjective fatigue. Our results are in good agreement with and complementary to known effects.

During prolonged cognitive tasks, several processes occur concurrently and directly impact performance, including fatigue. Indeed, prolonged cognitive activity often leads to a feeling of fatigue and is frequently accompanied by performance degradation [38], [39]. However, the effect of fatigue on performance is not always apparent. For instance, according to the "anticipatory regulation" hypothesis [8], [40], [41], subjective fatigue occurs before any adverse effects on the brain can be observed [42]

Our experimental task was designed to activate participants' working memory and required them to maintain a high level of attention throughout the experiment in order to successfully complete it. Papers [43], [44], [45] demonstrate that these two cognitive processes are closely related and influence each other.

The attention network in the human brain is a complex, highly organized structure involved in the regulation of attention processes, visual information processing, and memory. It is predominantly localized in frontal–parietal areas [46]. Attention is usually separated into top–down (dorsal attention system), in the sense that it is directed in accordance with our current goals, and bottom–up (ventral attention system), which is activated automatically regardless of these goals [45].

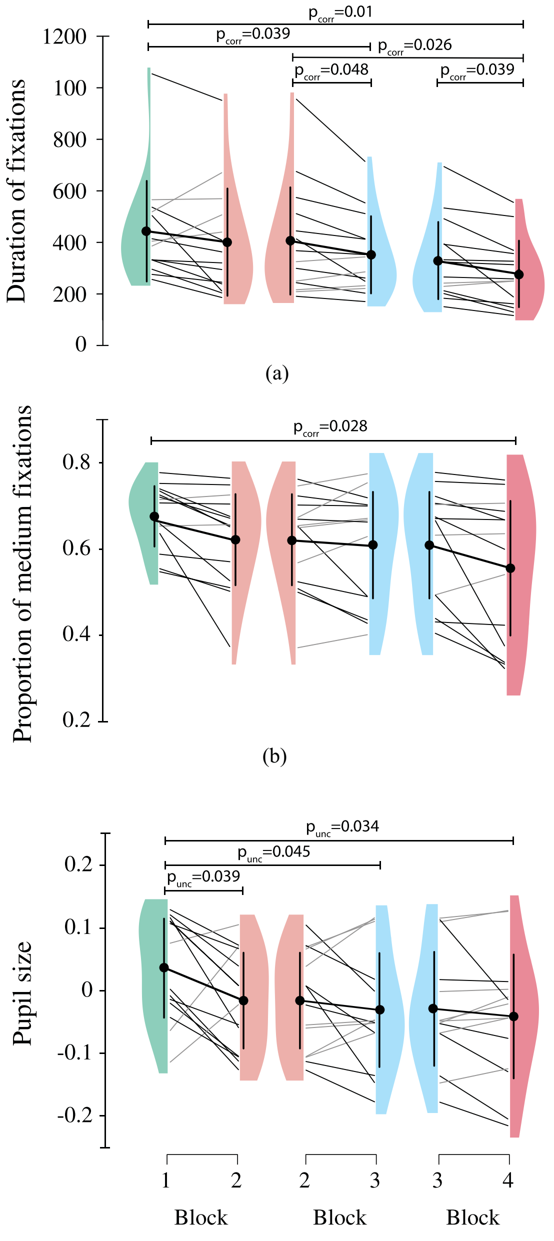
Working memory, on the other hand, is the ability to temporarily store and manipulate information to perform cognitive



(a) (b)

(c)

(d)



(a)

(b)

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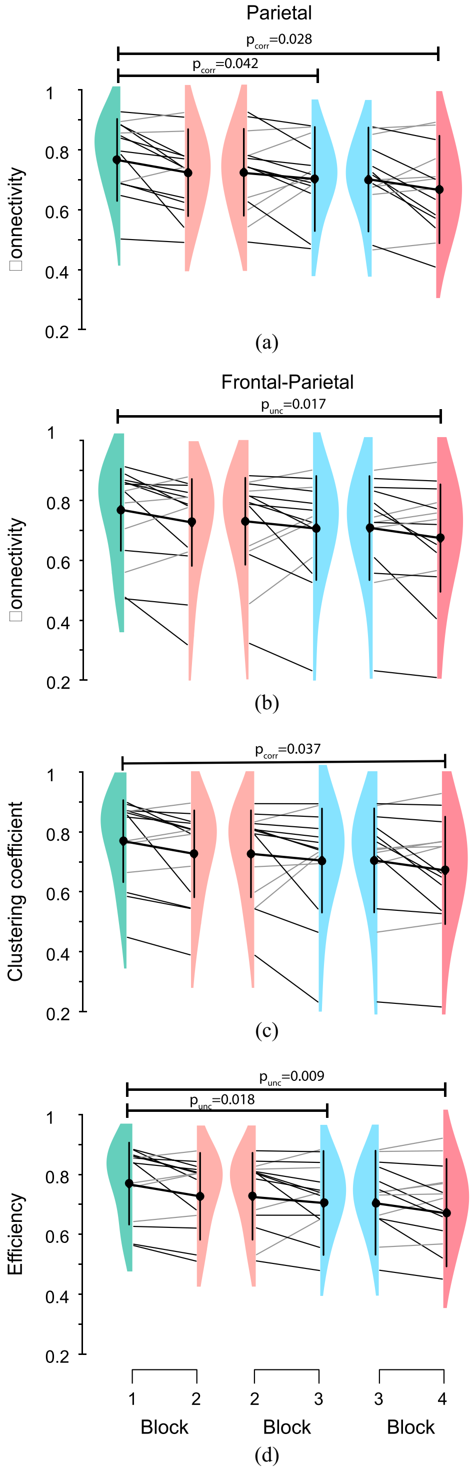
Fig. 3. Results on behavioral data. (a) Percentage of correctly solved task for different complexities. (b) Average response time for different complexities. (c) Dynamics of the average response time during the experiment for high and low complexities. (d) Dynamics of the difference between the average response times for high and low complexities during the experiment. Here, p_{corr} and p_{unc} are Holm–Bonferroni corrected and uncorrected on the multiple comparisons [12 comparisons for (c) and 6 comparisons for (d)] statistical levels in post hoc analysis, respectively (see Tables II and III).

Fig. 4. Dynamics of gaze fixations and pupil size during solving the task: (a) and (b) dynamics of the block-averaged duration of fixations and dynamics of the proportion of medium fixations relative to the total number of fixations; (c) dynamics of the block-averaged normalized pupil size. Here, p_{corr} and p_{unc} are Holm–Bonferroni corrected and uncorrected on the multiple comparisons (six comparisons) statistical levels of significance in posthoc analysis, respectively (see Table II).

tasks. The foundations of verbal working memory, for example, include the phonological storage and subvocal rehearsal mechanism, which depend on a complex prefronto-parietal network and left hemispheric speech areas of the brain [47].

We obtained that continuous task execution was associated with an increase in subjective fatigue and an increase in response time for low complexity tasks. Various theories have been proposed in the scientific literature to explain the decrease in productivity caused by mental fatigue [48]. One such theory is the resource theory. It attributes performance degradation to the overuse of a limited amount of resources that cannot be quickly recovered.

At the same time, tasks requiring conscious attention, according to the global neural workspace theory [49], activate a global neuranal workspace that integrates information from many different parts of brain networks. This integration allows



(a)

(b)

(c)

(d)

Fig. 5. Network measures of a brain functional network formed during solving the task. (a) and (b) Average connectivity within the parietal area and between the frontal and parietal areas. (c) and (d) Dynamics of global clustering coefficient and global efficiency during solving the task, respectively. Here, p_{corr} and p_{unc} are Holm–Bonferroni corrected and uncorrected on the multiple comparisons (six comparisons) statistical levels in posthoc analysis, respectively.

information to become available for conscious perception and further processing, including attention tasks.

Repeated reuse and depletion of limited cognitive resources can eventually lead to disruption, breaking down functional connections and forming a more disintegrated network structure. Such observations are common in research papers examining the relationship between brain network characteristics, fatigue, and performance [48], [50], [51], [52]. Specifically, the [50] study showed that mental fatigue increased reaction time and decreased network efficiency in the brain in participants taking a sustained attention test. EEG analysis revealed changes in the global topology of brain networks, indicating impaired functional connectivity and reduced global integration.

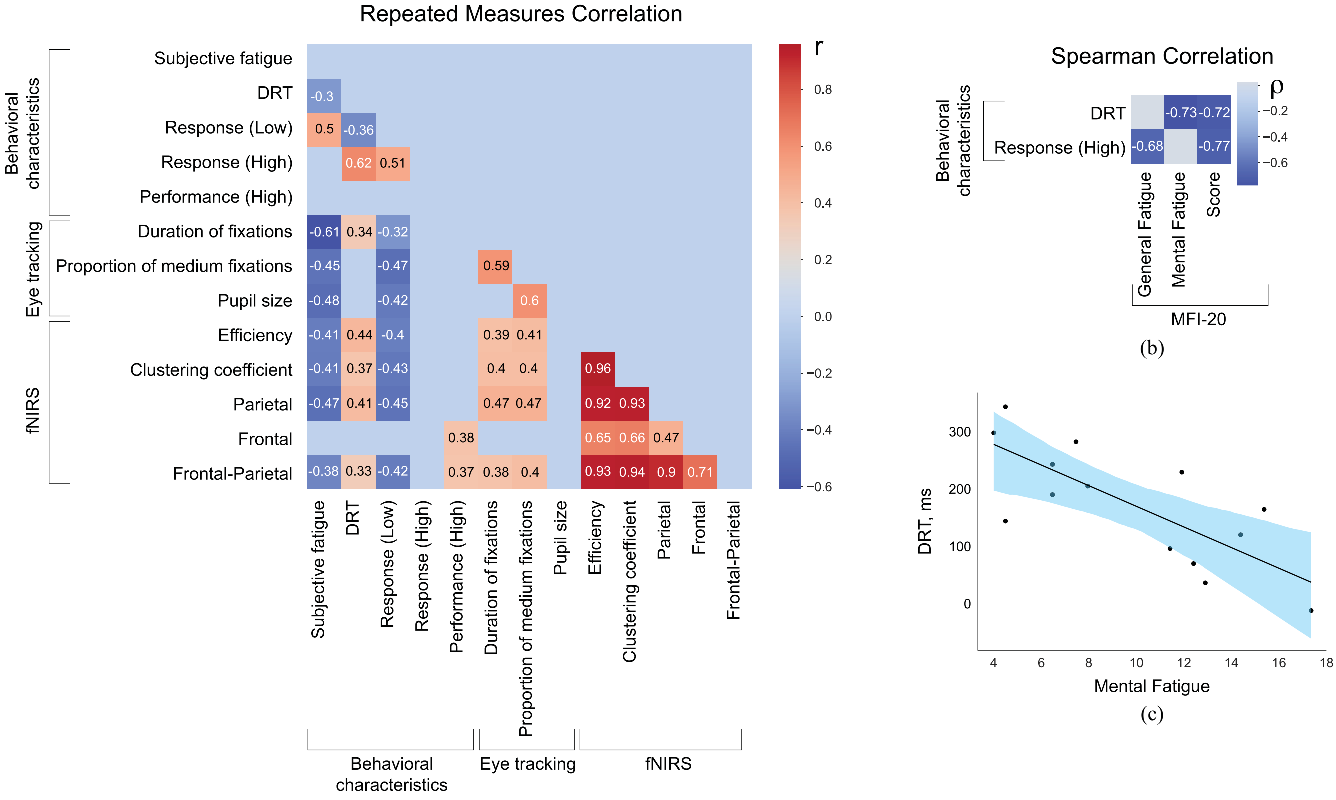
Many other works, also emphasize the relationship between topological characteristics of brain networks and fatigue. For example, Work [53] investigated the effect of fatigue on functional connectivity of the brain using resting-state connectivity analysis. The results showed that fatigue significantly impaired connectivity in the parietal area. Moreover, a study by [54] shows that frontoparietal brain subnetworks can adapt their topology to compensate for the cognitive decline caused by mental fatigue.

Indeed, several previous studies have shown that maintaining performance is possible due to compensatory increases in mental effort [8], [9], [55] despite increases in fatigue. Moreover, the authors of the study [9] have shown that compensatory effort may depend on task difficulty. The behavioral data in the mentioned paper shows that compensatory effort was higher for the difficult task than for the easy one. Successful completion of the task in our experiment requires maintaining a high level of attention. Several previous studies have shown that the activity of the frontoparietal network is crucial for maintaining sustained attention [55], [56], [57], [58]. Hence, the functional connectivity of this network can be impaired after long periods of sustained activation due to the associated mental load. This leads to decreasing performance of the frontoparietal network, which is confirmed by the results of the analysis of the network characteristics in the present work [see Fig. 5(b), where the decrease in connectivity of the frontoparietal network is demonstrated].

However, due to compensatory mechanisms, subjects managed to maintain a high proportion of correct answers during the experiment. At the same time, we observed a dependence of compensatory effort on task complexity, as in [9], which preserved the response time for tasks of high difficulty but increased the response time for simpler tasks.

We suggest that compensatory efforts in our experiment allowed for a reduction in the influence of fatigue when solving only high-complexity tasks by preserving the frontoparietal network efficiency, while for low-complexity tasks, the compensatory efforts were essentially less pronounced or absent altogether. This led to an increase in response time with increasing fatigue and should be accompanied by a decrease in the frontoparietal network efficiency. If this is true, then the change in the difference between the response times (DRT) for complex and simple tasks during the experiment should reflect a change in the frontoparietal network efficiency and the degree of compensatory efforts. Indeed, this hypothesis is supported by the significant positive correlation between DRT and the global efficiency of the frontoparietal network [see Fig. 6(a)].

We also found that the DRT averaged over the experiment negatively correlated with the average mental fatigue



(a) (b) (c)

Fig. 6. Results of correlation analysis. (a) Map of pair correlations between all characteristics that change during solving the task obtained using repeated measures correlation. (b) Correlation map between task-averaged behavioral characteristics and the average value of the MFI-20 questionnaire obtained using Spearman correlation. Here, Score is sum of the scores on all scales of MFI-20. (c) Linear regression obtained for the difference between the average response time for high and low complexities and the value of Mental fatigue. The blue area is a 95%-confidence interval. Here, the maps include only statistically significant correlations. The threshold for repeated measures correlation equals 0.05, and for Spearman correlation equals 0.01.

[see Fig. 6(b) and 6(c)]. This relationship complements the concept described above and emphasizes the relation with cognitive processes. Moreover, the strong correlation of DRT with mental fatigue suggests that DRT may be a useful biomarker for the design of brain–computer interfaces.

Such compensatory efforts may be related to the regulation of the level of top–down attention depending on the complexity of the task. Indeed, high-complexity tasks are characterized by higher demands on top–down attention and memory. In the context of global workspace theory, such tasks should be accompanied by stronger integration and dynamic interactions between different brain domains. Our results show that connectivity within frontal and between frontal and parietal areas is associated with accuracy on high complexity tasks. This can be interpreted as the integration of more extensive areas of the frontoparietal network and the recruitment of additional resources for complex tasks. At the same time, performance of low-complexity tasks is characterized by less activation of brain neural networks and lower requirements for top–down attention, which makes them more susceptible to the factor of fatigue.

We observed significant reductions in pupil size, fixation duration, and the proportion of median fixations. Importantly, these changes exhibited an inverse correlation with the reported levels of fatigue. These findings are consistent with prior research and contribute additional empirical confirmation of the association between the eye parameters under study and fatigue [36], [59], [60].

Another important result of this study is the relationships found between the characteristics of eye movements and the measures of the frontoparietal network [see Fig. 6(a)]. On one hand, these results confirm previously established patterns, and on the other hand, complement them. Specifically, we found that the global efficiency coefficient strongly correlates with the proportion of medium fixations during the experiment. Additionally, changes in the proportion of medium fixations correlate with connectivity within the parietal lobe and between the parietal and frontal lobes. The parietal lobe is well known to be involved in visual object processing, visual feature binding, and spatial perception [61], [62], [63]. Fixations of medium duration are often associated with cognitive processes [36]. Thus, this experiment confirms the relationship between fixations of medium duration and cognitive processes and supplements the knowledge with their connection to the efficiency of information transfer in the frontoparietal network.

A. Limitations

The main limitation of this work is the small sample size (14 participants). Another limitation is the specificity of the experimental task, which focused only on working memory. It remains unclear whether similar adaptation mechanisms take place in logic tasks, visual search, abstract thinking, and other cognitive processes. Third, in this article, we focused on group effects and did not analyze the behavior of each subject separately. In particular, the task difficulty was the same for all subjects, rather than being selected individually based on their working memory capacity. This could have affected the results of the analysis due to the small sample size and individual differences in working memory capacity.

The employment of fNIRS in our study imposed distinct limitations on the extent of our analysis. This method facilitated the observation of only superficial brain activity changes, effectively precluding access to the deeper brain structures. This restriction significantly limits our capacity to fully comprehend the intricate brain processes that underpin the cognitive functions being explored. Additionally, the optodes utilized in our study provided coverage for only specific segments of the cortex, specifically those associated with the frontoparietal network. Consequently, this selective coverage introduces constraints on the scope of our investigation.

V. CONCLUSION

We employed a combined approach involving functional near-infrared spectroscopy and eye-tracking techniques. We reconstructed functional brain networks and analyzed them using network metrics. Our results demonstrated that the compensatory effort triggered by fatigue is dependent on the task's difficulty and aims to maintain the efficiency of the frontoparietal network.

Finally, in this article, we discovered multiple biomarkers of fatigue and memory task performance using a comprehensive multimodal approach. We believe that the obtained results can be extremely useful in the development of brain–computer interfaces for fatigue control and workload balancing in education, as well as for diagnostic purposes in medicine.

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