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Methodology of the neurophysiological experiments with visual stimuli to assess foreign language proficiency

A. N. Pisarchik[1,2], *V. S. Khorev*[1], *A. A. Badarin*[1]✉, *V. M. Antipov*[1], *A. O. Budarina*[1], *A. E. Hramov*[1]

[1]Immanuel Kant Baltic Federal University, Kaliningrad, Russia
[2]Polytechnic University of Madrid, Spain
E-mail: alexander.pisarchik@ctb.upm.es, khorevvs@gmail.com, ✉Badarin.a.a@mail.ru, vantipovm@gmail.com, abudarina@kantiana.ru, aekhramov@kantiana.ru

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Abstract. *Aim* of this study is to compare different experimental paradigms and to determine parameters suitable for conducting a neurophysiological experiment with visual stimuli to assess foreign language proficiency and providing further time series analysis of electrical brain activity to reveal specific biomarkers. *Methods.* This paper explores the possibilities and limitations of various experimental studies using the metaanalysis paradigm. Statistical approaches are used to determine significance of the results. *Results.* We review the current state of research in the field of experimental works related to visual stimulus presentation and verbal performance acquisition. Generalizations and analytical estimates of the experimental parameters used in the studies are carried out to provide recommendations for future experimental research. *Conclusion.* In this area of applied research, we have developed experimental design and algorithms for working with multiple data sources. In addition, experimental encephalographic studies have been carried out, that allowed the optimal temporal structure selection.

Keywords: experimental design, metaanalysis, neuroscience, neurolinguistics, nonlinear systems.

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Introduction

The study of the principles of brain functioning for solving problems related to cognitive and emotional human activity during the educational process, the so-called neuropedagogy, is a very important area of modern research at the intersection of neuroscience, pedagogy and information technology [1–3]. Of particular interest is the application of neuroscience approaches in the framework of the development of linguistic abilities, which is important for improving the level of foreign language acquisition by students. Research in this area based on neurophysiological signals of the brain is aimed at developing methods for analyzing the human condition and optimizing the process of learning foreign languages [4–12].

Эффективные методики усвоения иностранных языков позволяют систематизировать накопленные знания, необходимые для выполнения различных трудовых функций в рамках практической или исследовательской деятельности. Skills and abilities, for example, such as: (1) competently systematize theoretical knowledge on the methodology of teaching a foreign language, (2) learn to independently set and solve professional tasks, (3) determine ways and methods of solving them, (4) be ready to use the acquired systematized theoretical and practical knowledge for solving professional tasks, they depend on the effectiveness of the chosen teaching methodology, which underlines the relevance of this study [11].

The demand for such studies is due to the need to create effective methods and devices for practical implementation in the educational process aimed at better and faster assimilation of foreign languages, as well as an objective assessment of the level of knowledge of the subject being tested, taking into account its neurophysiological features [13–17]. Publications in scientific journals devoted to the experimental study of various aspects of learning a foreign language have appeared for a long time. Since then, thanks to the efforts of scientists in the field of cognitive science, psychology and neuroscience, a rich theoretical base has developed, on the basis of which researchers are trying to understand the nature of higher nervous activity when communicating in a non-native language. One of the significant facts discovered as a result of recent studies is the different reaction time when switching from a native language to a non-native and vice versa, which indicates the presence of a stable neural network in the brain responsible for processing and forming speech in a non-native language. Experimental work on the search and stimulation of this network is of interest to neuropedagogics in order to improve the assimilation of a foreign language using various methods of neuroimaging [18–20].

The purpose of this study is to determine the parameters suitable for conducting a neurophysiological experiment with the presentation of visual stimuli in order to assess the level of proficiency in a foreign language. This will allow further analysis of time series of neurophysiological nature to identify specific biomarkers and conduct experiments using the selected parameters.

1. Methodology

1.1. Selection criteria. To review the literature, a search was conducted for published articles using the Google Scholar search engine. The review consists of two parts devoted to different aspects of the experimental study. The following terms were used in the search query: "image names "neuro-linguistics "linguistics "translation "bilinguals". After the initial search for these terms, the missing words and formulations suitable for further search queries in the texts of previously found articles were rechecked. After that, previously defined terms were clarified for a more complex search dedicated to the study of neuro-linguistics, and a search was conducted in the database. At both stages of the job search, they were considered relevant for review if we found one of the search queries or an equivalent reformulation in its title, annotation or keywords.

1.2. Data collection and analysis. At the first stage of the work devoted to the generalization of maps of brain regions corresponding to linguistic research, we tried to avoid the inclusion of studies with subjects with neurophysiological pathology, with the exception of works where the study of brain regions responsible for the violation of linguistic functions was carried out. Although several selected papers contained results for heterogeneous groups due to the design of the experiment, for this review we extracted information only about control groups, that is, subjects without pathologies. As for the part of the review devoted to the latest research and practical applications, we did not apply any additional restrictions to the protocol of the experiment, trying to cover all the trends that have appeared in the field of neurolinguistics in recent years.

Further analysis of the collected literature made it possible to classify various research methods. Most of the selected papers included quantitative research methods with homogeneous results. A comprehensive generalization of scientific approaches, taking into account the goals and results of linguistic experiments, allowed us to collect extensive material, which we systematized in the Table. (The number of trials is indicated by N_{T}, the duration of the stimulus is — T_{s}, the duration of the pause is— T_{p}, the language designations are given in accordance with the international codification ISO 639).

Table. Linguistic research using visual stimuli and receiving verbal responses

Publication	N_{T}/ T_{s}, мс/ T_{p}, мс	Goals and objectives	Languages	The results obtained
[4]	950/ 2000/ 1000	See the difference in reaction speed when switching the language	es ca kr	Detected a delay when switching languages
[5, 6]	384/ 250/ 500	Track the difference in the processing time of the stimulus when switching languages	nl en	Inhibition of attention when switching languages
[7]	108/ 1000/ 2000	Trace the difference when presenting numbers or images	de en	Naming a number does not carry semantic content
[8]	96/ 4300/ 180	To identify differences in activation in bilinguals and monolinguals	es ca	Bilinguals, when the name of the image is in their native or non-native language, have higher activation compared to monolinguals in 5 regions of the left hemisphere
[9]	120/ 2000/ 8000	Studying the effect of activation on the reaction rate when switching languages	jp en	A lexical solution, in which any activated meaning of a word causes the activation of a reverse response, leads to a negative relationship between the amount of activation and the reaction rate
[10]	360/ 1500/ 500	The difference between plural nouns in contexts where they were preceded by a color modifier	en	Color changes caused higher activation than similar differences for multiple objects

[12]	100/ 1500/ 250	Trace the change in evoked potentials when switching the language	nl en	The data of evoked potentials showed a tendency to decrease N400, which indicates that the participants used a post-lexical verification mechanism during the switching block
[13]	134/ 500/ 1000	Fix the separation of nouns and verbs	en	Delay in the presentation of verbs
[14]	240/ 3000/ 1500	Determine when and how L2 learners begin to affectively and semantically process L2 words	de nl	L1 and L2 are initially processed semantically and affectively through relatively separate channels, which are increasingly associated with the impact of L2
[15]	124/ 600/ 2400	Image naming analysis to investigate early effects of variables specifically related to visual, semantic, and phonological processing	en	The activation of the brain associated with the visual image appears in the occipital cortex approximately 100 ms after the start of the image presentation. After about 150 ms, semantic variables manifest in the left frontal parietal regions. Access to phonological information can begin in parallel with semantic processing about 150 ms
[16]	96/ 3000/ 1500	Testing the hypothesis of modulation of interference and inhibition effects when using the new L2 language	pl en	The L2 proficiency level does not modulate interference and braking effects
[17]	184/ 4000/ 2000	Testing the hypothesis that the brain networks that form the basis for L1 language proficiency are involved during the explicit study of a non-native L2 language	es eu	Electrophysiological responses during L2 processing, similar to L1 responses, can be seen after a few hours of training
[18]	80/ 3000/ 1000	Study of the impact in the form of actions of other agents, arbitrary switching when naming an object	hi en	External signals that are irrelevant to the task can influence the choice of language when arbitrarily naming objects.
[19]	576/ 1500/ 1200	Trace the difference between switching attention between languages	en ar	Delay when switching languages
[20]	48/ 3500/ 2500	Analysis of functional connectivity in trilingual	yue zh en	Effective connectivity analysis revealed a cortical-subcortical-cerebellar inhibitory control scheme in trilingual
[21]	336/ 1500/ 1000	Assessment of how bilinguals choose words in the appropriate language when reproducing and recognizing, minimizing the influence of a non-native language	nl en	It was found that switching the language was costly only for L1, but not for L2

[22]	550/ 5000/ 1000	To investigate the relative contribution of automatic processes (grapheme to phoneme conversion) and processes requiring attention (semantic involvement)	nl en	A fractal pattern of variability for naming words in Dutch and English is shown
[23]	300/ 1500/ 3000	Testing the hypothesis that the input data in semantic memory involved a certain heteromodal network center that integrates lexical search with the corresponding semantic content	en	An increase in the activity of the central part of the corpus callosum was revealed
[24]	1152/ 300/ 4000	Comparison of repetition and language change	de en	The delay while waiting for a change is lower than when simply switching the language
[25]	96/ 2000/ 1500	Comparison of responses in paired testing	zh en	Synchronization of responses for verbal and nonverbal response
[26]	384/ 3000/ 700	Testing the hypothesis of whether learning related to lexical selection is based on mistakes, and whether lexical selection is competitive by assessing the consequences of creating words for the subsequent production of semantic competitors	en fr es	After a verbal response in a language with a high degree of error (L3), the cost of a response in another language with a high degree of error (L2 compared to L1) was higher
[27]	768/ 2000/ by response	Determining the superiority of bilinguals over monolinguals, taking into account age	fr it	Bilinguals have an advantage in any age category, but young people cope with the task better
[28]	432/ 2000/ 1200	Compare the costs of switching the language and switching the concept	nd en zh	The cost of switching the concept is higher than switching the language
[29]	320/ 2000/ 2000	Comparison of language inhibition during switching	zh en	Non-native language is inhibited on switching, but not during reuse
[30]	96/ 800/ 1500	To investigate to what extent experimentally induced language modes affect the executive functions of bilinguals	en de	The frequency of language switching was a negative predictor of performance under conditions activating alternative and monolingual control modes
[31]	24/ 2000/ 3000	Search for areas of the brain responsible for language control	nd en	A change in activity in the primary somatosensory cortex was revealed
[32]	1448/ 2500/ 1000	Investigation of the interaction between cognitive and psycholinguistic factors underlying bilingual speech production	it de en zh sk	It is shown that the process of producing individual words in healthy adult bilingual people is influenced by the interaction between cognitive, phonological and semantic factors
[33]	224/ 500/ 3000	Comparison of efficiency in the presentation of monomorphemic and multimorphemic words	de	An increase in the number of errors in the presentation of multi-morphemic words was revealed

[34]	156/ 2500/ 250	Investigation of the relationship of cognitive switching during language change	zh ug	The duration of exposure to the minority language L1 and the age of language acquisition L2 affect language control in the process of speech production
[35]	31/ by response/ 0	Study of the difference in the performance of language learning at different ages	en zh	Foreign languages are studied with a large gap in productivity, and are served by fundamentally different mechanisms
[36]	183/ 3500/ 500	Consideration of the switching cost model and the reverse effect of language dominance	en zh	Asymmetric switching cost with higher L2 costs in congruent context compared to basic and non-congruent contexts
[37]	70/ 2500/ 1000	The study of whether bilingualism in close and distant language pairs affects language control and general cognitive processes	en ar fr	Stronger involvement of language control and areas of general cognitive control in close languages
[38]	100/ 1500/ 1200	Studying the effect of the extent to which the neural representation of a word is the same when it is being prepared for reproduction as a separate word, compared to when it is being prepared as part of a meaningful phrase	en	A strong asymmetry between nouns and adjectives was found, while the names of nouns are usually better decoded
[39]	144/ 2500/ 500	Explore the difference between accessing the meaning of a word and assembling its pronunciation	vi	It is shown that prosodification in Vietnamese is similar to Germanic languages, not Chinese
[40]	160/ 1500/ 1500	Study of brain activity when presenting captured visual images	en	Modulation of motor responses and cortical rhythms in the processing of captured visual images
[41]	286/ 5000/ 3000	Investigation of the entropy of responses when naming images	de	The delay in the name can be described by the entropy of the frequency of words in the language
[42]	128/ 1500/ 500	Comparison of statistical indicators in the recognition of different images	de	Statistically significant effects are shown in connection with delays and the degree of familiarity with words, visual complexity of images, psychological valence
[43]	96/ 2000/ 250	Research on the influence of language dominance on language recognition	zh ug	The initial age of L2 acquisition (but not recent familiarity with the language) and cross-modal language dominance contribute to variations in L2 recognition
[44]	48/ 2500/ 600	Studying the influence of an additional language on the cognitive perception of time	zh mn en	Learning an additional language can change the cognitive abilities of speakers if there are significant differences between L1 and L2

1.3. Materials of experimental studies. A number of experimental studies were conducted in which 15 non-smokers, without neurophysiological diseases, not undergoing drug treatment of volunteers aged 18 to 22 years with different levels of English language proficiency, who are not native speakers, which is comparable to the samples in the works [5, 6, 19]. All volunteers were asked to adhere to a healthy lifestyle (at least 8 hours of sleep, exclude alcohol consumption, exclude or limit the consumption of caffeine-containing products) for 48 hours before each experiment. The volunteers were familiarized in advance with the procedure of conducting the experiment and possible inconveniences, had the opportunity to ask questions and get satisfactory answers to them. Each subject filled out and signed an informed consent form to participate in the experiment. All experimental work was carried out in accordance with the requirements of the Helsinki Declaration.

The experiment was conducted as follows. The subject was sitting in a comfortable chair, and on the table in front of him there was a monitor (the distance from the screen to the eyes is 30–40 cm) and a microphone. During the experiment, brain activity was recorded using electroencephalography (EEG). For this purpose, the equipment at the disposal of the laboratory was used. Note that EEG signals give an idea of the electrical activity of the brain. An electroencephalograph «actiCHamp» manufactured by Brain Products, Germany, was used to register EEG activity. EEG signals were recorded for 64 channels according to the standard scheme «10–10». The grounding was located in the place of the electrode «Fpz», and the electrode, which served as a reference, was placed behind the right ear. To register the EEG, active Ag/AgCl electrodes «ActiCAP» were used, which were located on the surface of the scalp in the sockets of a special cap «EasyCap». To improve the quality of signals and ensure better conductivity, the scalp was previously treated with an abrasive gel "NuPrep and then the electrodes were installed using a conductive gel «Supervisor». During the experiment, the conductivity values on each of the EEG electrodes were monitored. Usually the values were less than 15 kOhm, which is sufficient for the correct operation of the active EEG electrodes.

2. Results

2.1. The number of trials used. When designing an experiment with human participation, experimenters must decide how many trials each participant will perform, as well as the number of participants. Most discussions of statistical power focus on sample size and involve a sufficient number of trials [45]. The study of the influence of both factors on statistical power is especially important when the variance within groups the number of participants is significant compared to the variance between participants. Existing data sets for experimental paradigms and methodologies should include reaction times, sensory thresholds for functional magnetic resonance imaging, MEG, EEG, and variance estimates within and between participants for each method. Nevertheless, even in articles published in prestigious journals, we do not always find a sufficient number of subjects, which significantly reduces the statistical power in the paradigms used.

In Fig. 1 the percentage distribution of the number of articles by the number of tests is presented. It is clearly seen that about half of the work was limited to the number of trials less than 100, which could have a negative impact on the significance and reproducibility of the results. It is worth noting the relatively small number of works with the number of tests above 500. This indirectly indicates that there is no need to carry out too many tests, as this can lead to negative consequences due to the accumulation of mental and physical fatigue [46]. Taking into account all of the above, we can conclude that the use of 100 to 500 tests is optimal in terms of experimental purity and statistical power.

2.2. The duration of the stimulus. On the one hand, the duration of the stimulus is limited by the speed of transmission and processing of visual information, which causes a

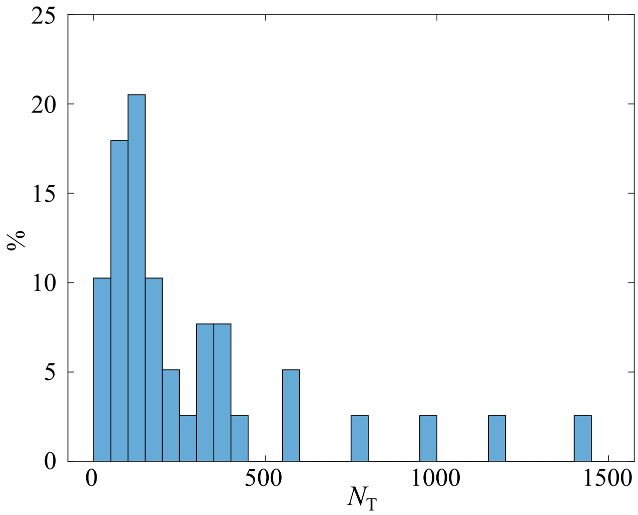


Fig. 1. Percentage of the number of papers versus the number of trials used

lower threshold of 200 ms [45, 46]. On the other hand, too long presentation of the stimulus leads to an increase in the cost of conducting the experiment and fatigue of the subject. In addition, visual perception adapts to its recent history. This is associated with the phenomenon of repetition suppression, a decrease in nervous reactions to repeated presentation of visual information compared to spontaneous visual input. The time scale during which the entire visual hierarchy is suppressed is configured to improve the time statistics of visual input functions that change rapidly in low-level regions, but are more stable in higher-level regions [47–49].

In Fig. 2, *a* shows the percentage distribution of the number of articles depending on the duration of the stimulus. It is easy to see that this distribution has a hilly appearance. The calculation of the agreement criterion χ^2 [50] does not refute the hypothesis that the data come from a normal distribution with an average value and a deviation estimated over the entire set at the significance level of $p < 0.05$. For an experimental study, it makes sense to limit ourselves to half of the distribution in the vicinity of the distribution maximum. Taking into account all of the above, we can conclude that it is desirable to use stimuli lasting from 1000 to 3000 ms.

2.3. Pause duration. The duration of the pause between stimuli greatly affects the concentration of the subjects' attention during the experiments with the presentation of images [51]. Studies using models of cognitive sets for simple nonverbal visual stimuli have determined the features of the dynamics of electrical oscillations in the range of α-rhythm in the cerebral cortex during the time periods between warning and target stimuli or between target and inducing stimuli [52]. In both cases, the phenomena of rhythm desynchronization in response to the presentation of the first stimulus are known, but in the middle part of the pause, on the contrary, synchronization is observed, which then noticeably decreases or changes to desynchronization immediately before the presentation of the next stimulus, as can be observed in Fig. 3. Note that the data for illustration in Fig. 3 were taken from the experiment, which is described in more detail in the section «Experiment design». This behavior is explained by a reaction induced by downward flows due to the duration of time intervals between target stimuli in the prefrontal cortex during the educational process [53–57].

In Fig. 2, *b* shows the percentage distribution of the number of articles by the duration of the pause between stimuli. This distribution does not have a clear configuration corresponding to any of the known distributions. Apparently, the researchers do not have a clear idea of the time

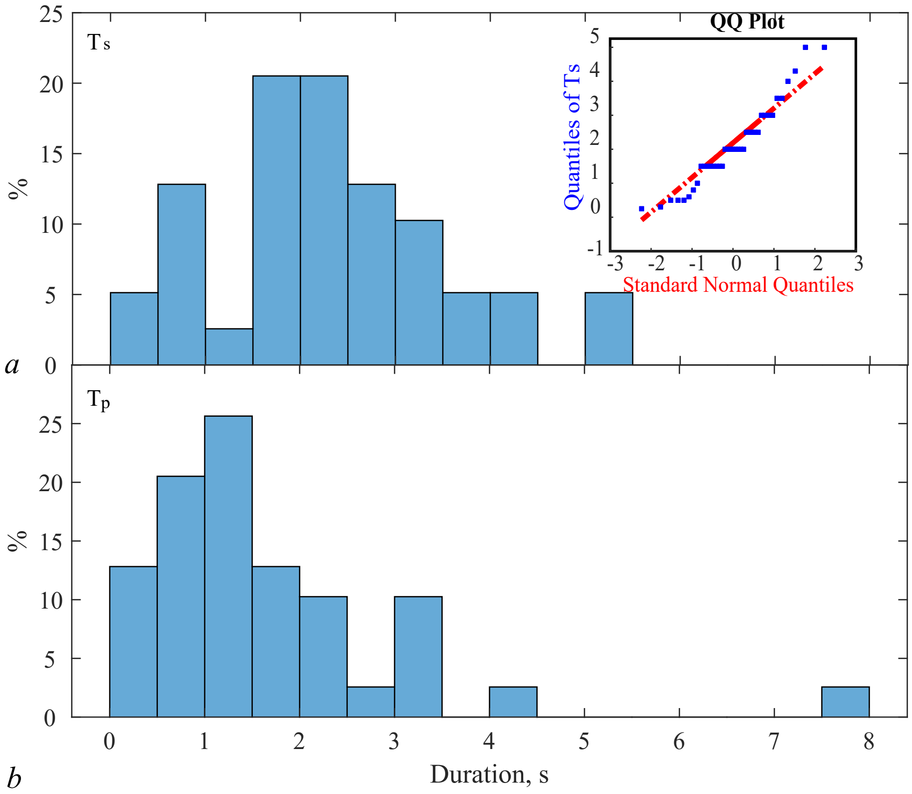


Fig. 2. — Percentage of the number of papers versus stimulus duration. QQ-plot for the stimulus vs normal distribution. *b* — Percentage of the number of papers versus stimulus and inter-trial pause duration (color online)

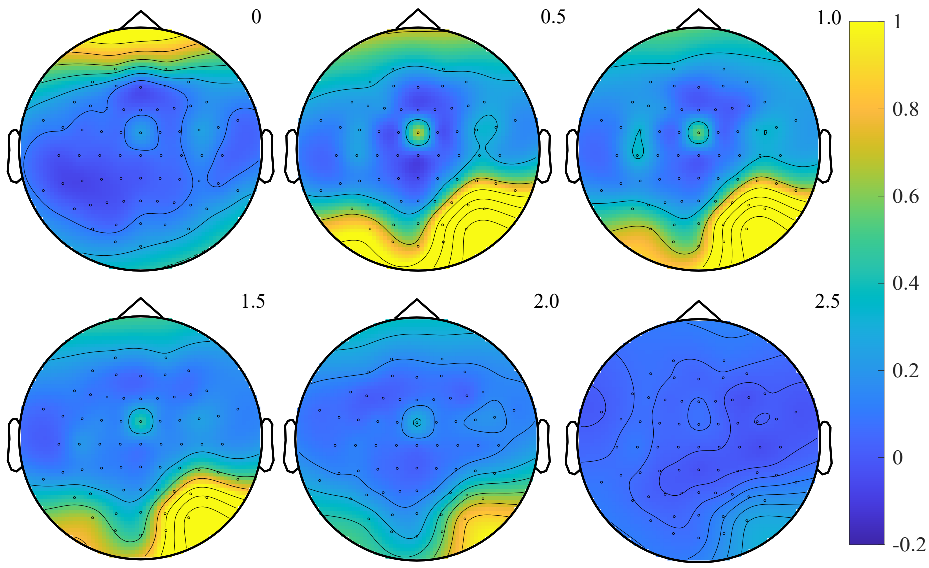


Fig. 3. Topogram of average trial activity in alpha band at the event-related synchronization/desynchronization for the pause. The plots refer to fixed latencies at 0–2.5 s with respect to the end of the stimulus. Colormap levels are presented in arbitrary units relative to the prestimulus baseline (color online)

required to switch to a new stimulus and sufficient to maintain the subject's attention on the task. For an experimental study, it makes sense to consider part of the distribution for intervals involving at least several works. Taking into account all of the above, we can conclude that it is desirable to use a pause duration from 500 to 3000 ms.

2.4. Localization of brain activity areas involved in the processing of stimuli and the formation of a verbal response in a foreign language. In the works of [8, 58] in the search for synaptic solutions after correction for multiple comparison throughout the brain, it was found that the areas activated by naming the visual image and verbal response included precentral and postcentral gyri, temporoparietal lobes, precentral and postcentral furrows, cerebellum, left thalamus and additional motor cortex. In addition, involvement of the left anterior lobe, anterior lumbar gyrus, dorsal premotor cortex, left superior temporal gyrus, left frontal lobe and cerebellum was noted. In the work of [15], the main changes were also observed in the left frontal-parietal regions, and in the work of [20] — in the cortical-subcortical-cerebellar network.

2.5. Experiment design. In connection with the above, it is recommended to use intermediate testing to assess the psychophysiological state of students while performing exercises in the course of experimental research. One of the most well-proven methods — for assessing the current level of fatigue — uses a subjective scale of multidimensional fatigue assessment (MFI-20) [59], consisting of 20 points and allowing you to assess fatigue on five scales: general asthenia, physical asthenia, decreased motivation, decreased activity, mental asthenia. MFI-20 provides a comprehensive assessment of the fatigue of the subjects.

A good alternative is a test for assessing subjective criteria of physical and mental condition, based on the assessment of the condition using a visual analog scale [60]. This test is quite suitable for quantifying the relationship of various aspects of fatigue during EEG recording experiments when performing various tasks [61]. In addition, it seems promising to use the NASA TLX (Task Load Index) test [62] for subjective multifactorial assessment of workload during task execution. At the same time , the assessment is carried out in the following areas: mental load, physical load, lack of time, effort, efficiency, level of discontent [63, 64].

As a result of generalization and analysis of experimental and theoretical scientific research related to the presentation of visual stimuli and the receipt of verbal responses, a design of a neurophysiological experiment was proposed in linguistics. The time structure of the experiment is shown in Fig. 4.

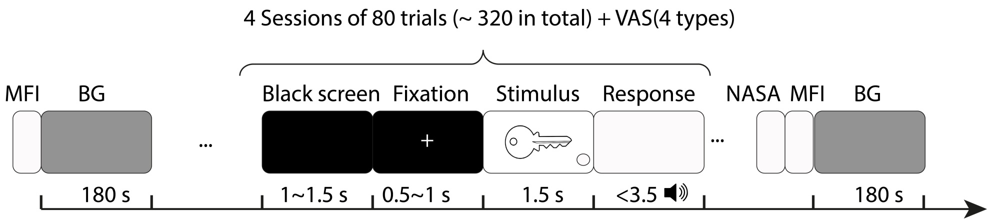


Fig. 4. Time structure of the experiment

1. The study begins with an assessment of the current level of fatigue using a subjective multidimensional fatigue assessment scale (MFI-20), consisting of 20 points and allowing you to assess fatigue on five scales: general asthenia, physical asthenia, decreased motivation, decreased activity, mental asthenia. To pass the test, the subject must be given an answer from 1 to 5, where 1 is — «Yes, it's true», and 5 is — «No, it's not true», to each of the statements presented. MFI-20 provides a comprehensive assessment of fatigue with special attention to the fatigue experienced by subjects [59].
2. This is followed by a 3-minute recording of background activity, during which the subject is asked to relax and not focus on anything.

3. This is followed by four blocks /sessions of 80 trials with the presentation of visual images.

   (a) The composition of each trial includes:
      i. showing a black screen during 1–1.5 c;
      ii. showing the cross for fixing during 0.5–1 c;
      iii. presentation of the stimulus in the form of a visual image/picture, accompanied by a light indication in the lower right corner during 1.5 c;
      iv. waiting for the verbal response of the subject, accompanied by a white background for up to 3.5 seconds, while the transition to the next trial can be carried out earlier if the verbal response is fixed.

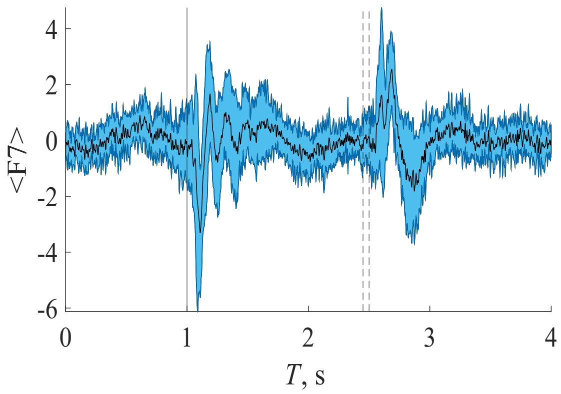
   (b) At the end of the block consisting of 80 trials, the subject passes a test each time to assess the subjective criteria of physical and mental condition, based on the assessment of the condition using a visual analog scale [60]. It consists of 4 (four) characteristics with corresponding scales:
      i. physical fatigue;
      ii. mental fatigue;
      iii. effort — evaluation of the amount of effort applied to maintain high performance of the task;
      iv. level of interest — assessment of the subject's interest in the task being performed.

   (c) Upon completion of four blocks (320 trials), the subject passes the NASA TLX (Task Load Index) test, used for subjective multifactorial assessment of workload during the task [64]. The assessment is carried out in the following areas: mental load, physical load, lack of time, effort, efficiency, level of discontent.

   (d) Next, the subject re-passes the fatigue assessment test (MFI-20).

   (e) The end of the experiment is accompanied by a 3-minute recording of background activity.

2.6. The results of the experiment. The sets of EEG trials obtained during the experimental study were pre-processed, including the removal of oculomotor artifacts and high-frequency noise. The data were averaged for each subject individually across all trials. The average



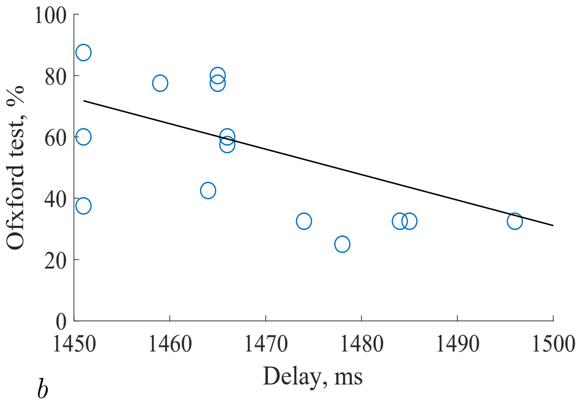


Fig. 5. *a* — Mean EEG response pattern from the F7 channel averaged over subjects, dash lines confine the delay interest interval. Mean ± SD. *b* — Linear fit of the dependence Oxford test % on the EEG delay (color online)

trial for all subjects is shown in Fig. 5, *a*. The vertical line shows the moment of presentation of the stimulus. The area corresponding to the time of 1450–1500 ms after the presentation of the stimulus may potentially be the most interesting from the point of view of assessing a person's linguistic abilities to learn foreign languages. The time corresponding to the position of the maximum signal in this range can be considered the delay time between the presentation of the stimulus and the processing of information to form a verbal response. In particular, the delay in the position of the maximum absolute value of the EEG signal from channel F7 in this range is negatively correlated (Pearson's cross-correlation coefficient $r = -0.5187$, the significance level of the coefficient $p = 0.0476$, Fig. 5, b) with an assessment of the level of knowledge of the test taker obtained during the passage of the vocabulary test [65]. The F7 lead corresponds to the Broca's area, which is the motor center of speech responsible for speech reproduction [66].

Conclusion

A detailed review of the literature of the current state of research in the field of experimental scientific research related to the presentation of visual stimuli and the receipt of verbal responses is carried out. Based on the analysis of the available literature, a design of an experiment in neuro-linguistics has been developed and algorithms have been created that allow working with multiple data sources. The conducted experimental studies made it possible to determine the optimal time structure and develop software for conducting EEG experiments and subsequent data processing.

In addition, generalizations of the obtained results and analytical estimates of experimental parameters allowed us to form recommendations for future experiments. In particular, it is shown that the use of 100 to 500 tests is optimal in terms of experimental purity and statistical power. It is desirable to use stimuli lasting from 1000 to 3000 ms with pauses between them from 500 to 3000 ms. At the same time, it is highly desirable to vary the intervals to prevent negative effects in the alpha rhythm associated with rhythmic repetition. In the course of the conducted experimental tests, promising indicators for assessing linguistic abilities were identified. A significant negative correlation was also found between the delay of peak activity in the Broca's area with the F7 lead and the assessment of the level of knowledge of the vocabulary test in the subject.

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