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Studying behavioral performance and neural activity during a prolonged visual task

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ABSTRACT

In this study, we analyzed the behavioral characteristics of the subjects (response time to visual stimuli and the correctness of interpretation), as well as brain activity at the sensory level when classifying repeatedly presented ambiguous images. We showed that the reaction time decreased for both LA and HA stimuli with the task completion time. In addition, the distribution of perception errors decreased for HA stimuli, but not for LA stimuli. At the sensory level, we found an increase in EEG power in the frequency range of 9-11 Hz with an increase in the task execution time.

Keywords: signal analysis, electromyograms, visual stimuli, cognitive load

1. INTRODUCTION

Sensory processing is a fundamental function of the brain that allows us to interact more easily with each other and with the environment. Thus, the study of processes of perception and processing of external information by the human brain is an urgent problem in neuroscience.[1–10] In everyday life, we collect sensory data and process it for interpretation and decision-making.[11] The accuracy and timeliness of our decisions depend on the speed and correctness of sensory processing. The effectiveness of sensory processing, in turn, is determined by a number of exogenous (external) and endogenous (internal) factors.[12] In particular, the exogenous component reflects the quality of touch input. Thus, when faced with unambiguous information, we can easily interpret it. On the contrary, when information becomes ambiguous, its interpretation requires more effort.

In turn, the endogenous component depends on a person's condition, on his attention, fatigue and subjective experience.[13] In many experimental studies that used ambiguous stimuli, it was found that endogenous effects were especially pronounced when the quality of sensory information was low.[14] Therefore, the observer should focus to gather more information to make the right decision, relying on personal experience to extrapolate limited information or eliminate its ambiguity.

The conditions under which the observer receives and processes information are also important. For example, driving a car at high speed in rainy weather at night requires very fast processing of low-quality information. Performing monotonous tasks with increased responsibility (for example, when piloting an airplane or analyzing indicators at a power plant) also requires maintaining high productivity and readiness for decision-making. In these stressful conditions, the influence of exogenous and endogenous factors on the probability of perception errors should be taken into account. Therefore, knowing and monitoring these factors can help predict perception errors and reduce their likelihood.

In this paper, we examined how the power of the EEG in the prestimulus state predicts behavioral characteristics during the solution of a long monotonous task.

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2. METHODS

2.1 Experimental procedure

Twenty healthy volunteers (nine women, 26-35 years old) with normal or adjusted to normal visual acuity participated in the experiments after providing written informed consent. They were familiar with the experimental task and had not participated in such experiments for the past six months. All experimental work was carried out in accordance with the requirements of the Helsinki Declaration and approved by the local Research Ethics Committee of Innopolis University.

The Necker cube was used as the visual stimuli.[15] It represents itself a cube with transparent faces and visible edges; an observer without any perception abnormalities sees the Necker cube as a 3D-object due to the specific position of the cube's edges. Bistability in perception consists in the interpretation of this 3D-object as to be either left- or right-oriented depending on the constrast of different inner edges of the cube. The contrast $a \in [0, 1]$ of the three middle lines centered in the left middle corner was used as a control parameter. The values $a = 1$ and $a = 0$ correspond, respectively, to 0 (black) and 255 (white) pixels' luminance of the middle lines. If a is close to 0 or 1, such a Necker cube is easily interpreted as either right-oriented or left-oriented. For $a \sim 0.5$, identifying the orientation of the Necker cube becomes difficult, since such an image has a high level of ambiguity. During the experiment, the subject was randomly shown 400 cubes of Necker with different values of the parameter a.

Participants of the experiment were instructed to press either the left or right key depending on the first impression of the orientation of the Necker cube. Since the perception of the current cube can be influenced by previously demonstrated Necker cubes, the length of the visual stimulus representation varied in the range of $1 - 1.5$ s. Also, a random change in the control parameter a also prevented the stabilization of perception. In addition, abstract images were exhibited for about $\gamma = 3.0 - 5.0$ between demonstrations of the Necker cube image to eliminate the "memory effect".

The EEG signals were recorded using the monopolar registration method and the classical extended ten–ten electrode system. We recorded 31 signals with two reference electrodes A1 and A2 on the earlobes and a ground electrode N just above the forehead. The signals were acquired via the cup adhesive Ag/AgCl electrodes placed on the "Tien–20" paste (Weaver and Company, Colorado, USA). Immediately before the experiments started, we performed all necessary procedures to increase skin conductivity and reduce its resistance using the abrasive "NuPrep" gel (Weaver and Company, Colorado, USA). The impedance was monitored after the electrodes were installed and measured throughout the experiments. Usually, the impedance values varied within a 2–5 kΩ interval. The electroencephalograph "Encephalan-EEG-19/26" (Medicom MTD company, Taganrog, Russian Federation) with multiple EEG channels and a two-button input device (keypad) was used for amplification and analog-to-digital conversion of the EEG signals. The raw EEG signals were filtered by a band-pass filter with cut-off points at 1 Hz (HP) and 100 Hz (LP) and by a 50-Hz notch filter by embedded a hardware-software data acquisition complex.

We segmented EEG signals into 4-s trials, where each trial was associated with a single presentation of the Necker cube and included a 2-s interval before and 2-s interval after the moment of the stimulus demonstration. We calculated the wavelet power for each trial in the $4 - 40$ Hz frequency range using the Morlet wavelet, while the number of cycles n was defined as $n = f$, where f is the signal frequency. Finally, we calculated event-related spectral perturbation, ERSP, by normalizing the wavelet power estimates W to the wavelet power of 40-s resting-state EEG as $ERSP = (W - W_{rest})/W_{rest}$.

2.2 Statistical analysis

We checked how the reaction time (RT), error rate (ER) and presentation time (PT) changed at four intervals, using additional control of orientation and ambiguity of the stimulus. We performed a repeated analysis of ANOVA with interval (1-4), ambiguity (HA and LA) and orientation (LO and RO) as internal factors. To obtain significant main effects, we conducted a post-hoc analysis using parametric or nonparametric tests, depending on the normality of the samples. Normality was determined using the Shapiro-Wilk test.

Statistical analysis of brain activity was carried out by the power of wavelets at the level of the subject, averaged by trials and by prestimulus wavelet power. The contrasts between the four intervals were tested for statistical significance using a permutation test combined with cluster correction for multiple comparisons. In particular, F-tests compared four sets of wavelet power for all (channel, frequency)-pairs. The elements that passed the threshold value corresponding to the value $p = 0.001$ (one-tailed) were labeled together with neighboring elements and were collected into separate negative and positive clusters. The minimum number of required neighbors was set to 2. The F values in each cluster were summed and corrected. The maximum sum was introduced into the permutation structure as a test statistic. A cluster was considered significant when its p value was below 0.01. The number of permutations was 2000.

All the described operations were performed in Matlab using the Fieldtrip toolbox.[3,7]

3. RESULTS

Observing behavioral reactions, we found that the decision-making time decreases with the task completion time for both HA and LA stimuli (Fig. 1, A). At the same time, the subjects improved the correctness of the interpretation of HA stimuli, but the result remained the same for LA stimuli (Fig. 1, B).

Analysis of the spectral power of the EEG at the sensory level revealed an increase in the power in the prestimulus state in the frequency range of 9-11 Hz with the time of the task (Fig. 2). Finally, we found that the power of the EEG in the prestimulus state negatively correlates with the decision time for stimuli LA and the number of erroneous responses to stimuli HA.

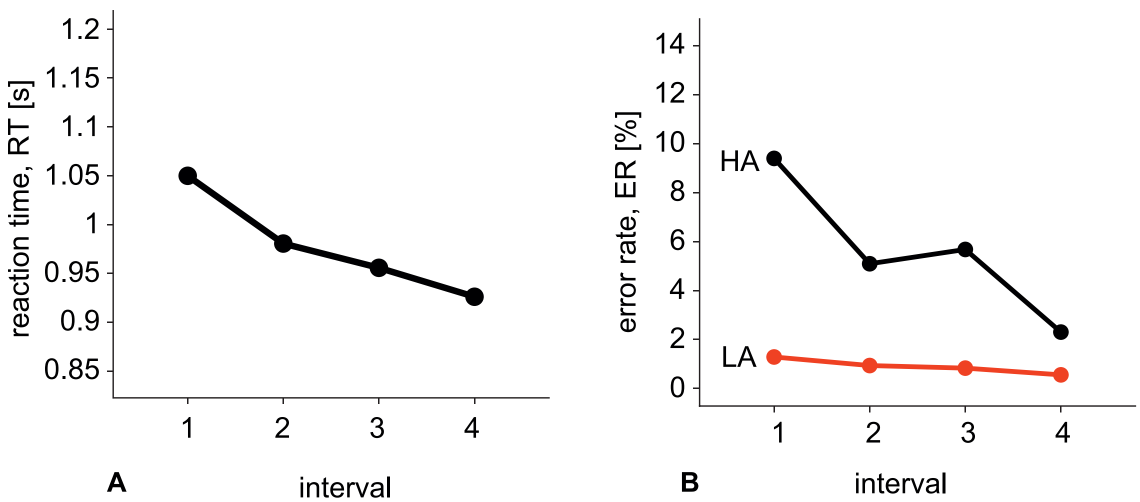

Figure 1. (A) The median value of the decision time regarding the orientation of the visual stimulus for 4 intervals. (B) Error rate for HA and LA stimuli for 4 intervals

First, we assumed that the power of the EEG in the prestimulus state reflects changes in the human condition. This condition, in turn, affected the processing performance of the current visual stimulus. Thus, our results showed that the high power of the EEG before the presentation of the stimulus in the range of 9-11 Hz predicted a faster decision-making time and greater accuracy. It is worth noting that we compared the EEG power and behavioral assessments between time segments, each of which lasted 10 minutes. Therefore, we have associated the described effects with slow changes in the observer's state. Together, we proposed a possible application of our results in passive brain-computer interfaces for monitoring the human condition and predicting the speed of decision-making and the accuracy of information interpretation.

The decision-making time may decrease due to neural adaptation, which occurs when the same visual stimulus is repeatedly presented within a short interval and causes a decrease in the neural response to a repetitive versus non-repetitive stimulus.[16] It is believed that neural adaptation occurs at least as a result of two types of neural activity. One explanation is that only that part of the activity that belongs to the ensemble of neurons is sensitive to the recognition of stimuli. Thus, neurons that are not critical for recognizing a stimulus decrease their responses when the stimulus reappears, while, on the contrary, populations of neurons carrying important

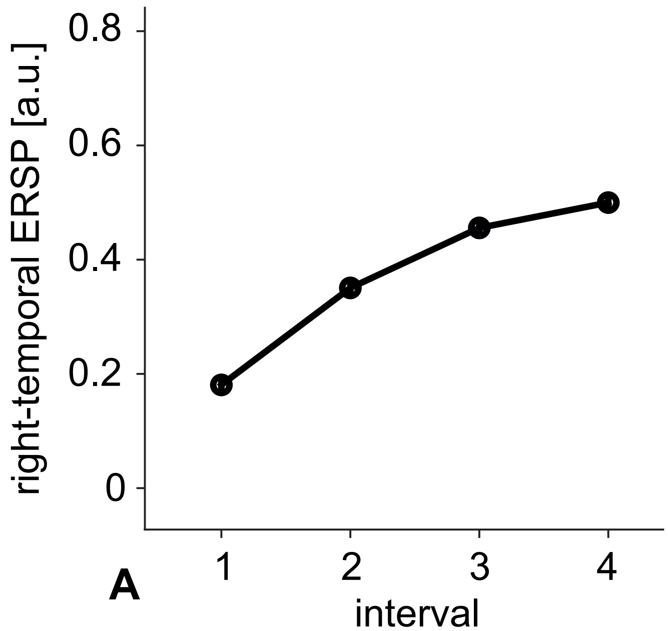

Figure 2. Change of ERSP in the right temporal region of the brain depending on the interval of the experimental session

information continue to give a stable response. As a result, the average speed of interpretation decreases due to the repetition of the stimulus.[17] Neural adaptation affects the response of neurons in the occipital,[18] parietal[19] and frontal[20] regions of the cerebral cortex. An increase in the power of the EEG in the prestimulus state may reflect the preliminary activation of sensory neurons.

Another potential explanation is the vital role of alpha range fluctuations for visual perception. Our results showed that an increase in power in the range of 9-11 Hz correlates with an increase in visual information processing performance. On the contrary, many studies have reported negative effects of alpha power on processing performance. The role of alpha-band fluctuations largely depends on the brain region. For example, the authors[21] provided evidence that alpha oscillations in the right brain region play a crucial role in suppressing habitual modes of thinking, thereby developing creative cognition. Other work has shown that observing the Necker cube can improve the solution of subsequent creative tasks.[22] In accordance with these works, we assumed that the increase in power in the right temporal region in the range of 9-11 Hz reflects the developing ability to suppress obvious associations. According to,[22] it can be a biomarker of neural processes that contribute to solving creative tasks.

Summing up, we can say that an increase in EEG power in the prestimulus state may reflect neural adaptation in the sensory regions of the brain encoding the morphology of the Necker cube, which explains the negative correlation between EEG power and the time of decision-making about LA stimuli. At the same time, the time of making a decision about HA stimuli also decreases with the time of task completion, but hardly correlates with the EEG power before the stimulus is presented. This behavioral effect is probably the result of neural processes acting after the presentation of the stimulus, and depends on integrative dynamics, and not on the modulation of EEG power in a certain area.

After studying the error rate, we found that the observer reacted more correctly to the LA stimuli. The number of erroneous answers is less than 2 % and remains unchanged during the experiment. On the contrary, the number of incorrect responses to HA stimuli decreased with the time of task completion and negatively correlated with the EEG power before the stimulus was presented in the range of 9-11 Hz.

4. CONCLUSION

In the process of classifying the Necker cube, the subjects reduce the decision-making time with the task completion time, regardless of the ambiguity of the stimulus. They also improve the correctness of interpretation only for stimuli with a high level of ambiguity. EEG analysis showed that the power in the prestimulus state in the alpha range increases with the time of the task. We found that the power of the EEG in the prestimulus state negatively correlates with the decision time for stimuli with a low level of ambiguity and the number of erroneous responses to ambiguous stimuli.

Our results can help to identify the links between the human condition and its effectiveness in solving current problems. This is important for the BCI to strive not only to detect, but also to predict human conditions. Such BCIs will lead to the emergence of artificial intelligence systems that help or warn when a high probability of critical errors is detected.

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