PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Effect of the previous stimulus on the processing of the current stimuli during their repetitive presentation

Kuc, Alexander, Maksimenko, Vladimir

Alexander Kuc, Vladimir Maksimenko, "Effect of the previous stimulus on the processing of the current stimuli during their repetitive presentation," Proc. SPIE 12194, Computational Biophysics and Nanobiophotonics, 121940N (29 April 2022); doi: 10.1117/12.2626391

Event: XXV Annual Conference Saratov Fall Meeting 2021; and IX Symposium on Optics and Biophotonics, 2021, Saratov, Russian Federation

Effect of the previous stimulus on the processing of the current stimuli during their repetitive presentation

Alexander Kuc[a] and Vladimir Maksimenko[a,b,c]

[a]Immanuel Kant Baltic Federal University, Nevskogo St, 14A, Kaliningrad, Russia
[b]Saratov State Medical University, Bolshaya Kazachia Str. 112, Saratov, Russia
[c]Innopolis University, Universitetskaya St, 1, Innopolis, Tatarstan Russia

ABSTRACT

In this study, we analyzed the effect of the ambiguity of the previous visual stimulus on the response time taken to process the current visual stimulus. Our experimental paradigm included the repeated presentation of ambiguous Necker cubes images with varying degrees of ambiguity. We studied the response time and the time-frequency features of EEG signals, reflecting the influence of the "sensory prehistory" on the current stimulus processing.

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

1. INTRODUCTION

The study of processes of perception and processing of external information by the human brain is an urgent problem in neuroscience.[1–10] To interact with the external environment and form a view of the surrounding world, the human brain uses a universal architecture based on the hierarchical organization of cognitive processes, as well as the interaction of processes at various levels of hierarchy. The details of incoming sensory information are processed at low levels of cognitive processing, and at high levels, the received information is interpreted as a whole.[11] There is an opinion that the brain uses acquired knowledge along with sensory data to create an accurate representation of the external environment.

In the hierarchical architecture of sensory information processing, the acquired knowledge is considered as high-level processes that influence lower-level processes. Some studies show that acquired knowledge forms patterns of sensory stimuli, and the brain, in turn, compares patterns coming from high to low levels of processing with external sensory information, while signals going in the opposite direction encode errors in matching information with existing patterns.[12–14] Many studies show the interaction and evidence of the formation of these processes at different levels of processing steps,[15] however, the exact mechanism for comparing external sensory information with templates has not been disclosed.

In this study, the subjects were repeatedly shown ambiguous visual stimuli, Necker cubes, with different levels of ambiguity (LA - low ambiguity, HA - high ambiguity). While the subjects reported their first impression of the orientation of each visual stimulus (left-oriented or right-oriented), we recorded the EEG signal and the time that the subject spent interpreting each stimulus (RT, reaction time). The demonstration of the same visual stimulus several times in a row causes neural adaptation, which, in turn, causes a decrease in the neural response to repeated stimuli.[16] This effect corresponds to the formation of stimulus patterns.[17,18] Thus, we examined the effect of previous stimulus ambiguity on the current stimulus processing in the case of both LA and HA stimuli. Generally, the interpretation of HA stimuli takes a longer time than the interpretation of LA stimuli. Since LA and HA Necker cubes have almost the same morphology, we assume their similar processing at low levels. At the same time, we suppose that the interpretation of the HA stimulus involves higher levels; consequently, at these levels, its processing requires a higher neural response. Finally, we assume that the HA stimulus pattern appears at hierarchically higher levels of processing than the LA pattern. As a result, the HA and LA patterns may affect the current processing of stimuli in different ways.

Further author information: (Send correspondence to A. Kuc)
A. Kuc: E-mail: kuc1995@mail.ru, Telephone: +7 927 221-32-93

Computational Biophysics and Nanobiophotonics, edited by Dmitry E. Postnov, Boris N. Khlebtsov,
Proc. of SPIE Vol. 12194, 121940N · © 2022 SPIE · 1605-7422 · doi: 10.1117/12.2626391

2. METHODS

2.1 Experimental procedure

Twenty healthy subjects (11 men and 9 women) aged from 26 to 35 years with normal or adjusted to normal visual acuity took part in the experiments. All of them gave written informed consent in advance. All participants were familiar with the experimental task and had not participated in such experiments in the last 6 months. The experimental studies were conducted in accordance with the Helsinki Declaration and approved by the local Research Ethics Committee of Innopolis University.

The Necker cube was used as the visual stimuli.[19] 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.[20] 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.

The recorded EEG signals were segmented into 4-second recordings, where each recording was associated with one demonstration of the Necker cube, including a 2-second interval before and a 2-second interval after the demonstration of the Necker cube. We calculated the spectral power for each test in the frequency range of $4 - 40$ Hz using the Morlet wavelet transform.[21] The number of cycles (n) was defined as $n = f$, where f is the frequency of the signal.[22] The wavelet analysis was performed in the Matlab environment using the Fieldtrip toolkit. Intervals of 0.5 s on each side of the recording were reserved for calculating the power of the wavelet. As a result, we considered the power of the wavelet at the interval of 3 seconds, including the prestimulus state (from -1.5 s to 0) and the activity associated with the stimulus (from 0 to 1.5 s). For the received wavelet power, we considered the event-related spectral perturbation (ERSP) using the normalization [stimulus–related activity - prestimulus state]/prestimulus state.

Two types of stimuli LA and HA were grouped and separated by conditions according to the ambiguity of the previous stimulus. Not only the ambiguity of the previous stimulus (the first previous one) was introduced into consideration, but also the ambiguity of the stimulus presented two cubes earlier (the second previous one). As a result, we considered four conditions for cubes LA and HA:

- condition 1 – both previous cubes have a low level of ambiguity (LA–LA);
- condition 2 – the first previous cube has a low level of ambiguity, and the second previous cube has a high level of ambiguity (HA–LA);
- condition 3 – the first previous cube has a high level of ambiguity, and the second previous cube has a low level of ambiguity (LA–HA);
- condition 4 – both previous cubes have a high level of ambiguity (HA–HA). To keep the number of EEG recordings constant depending on the conditions and the subjects, we selected 16 events for each condition.

2.2 Statistical analysis

Statistical analysis at the group level was carried out for the values of the median reaction time, the median time of presentation of the visual stimulus and the ratio between left- and right-oriented visual stimuli, as well as the ratio between the stimuli LA and HA. The main effects were evaluated using multivariate variance analysis with the correction of the Greenhouse-Geisser. We performed post hoc analysis either using the Student's t-criterion for dependent samples, or using the Wilcoxon criterion, depending on the normality of the samples. Normality was tested using the Shapiro-Wilk test. We conducted a statistical analysis using the SPSS software.

Spectral power and ERSP were compared for different experimental conditions in the time, spatial and frequency domains using a t-test for dependent samples. Correction of multiple comparisons was based on the cluster permutation test and the Monte Carlo randomization method. The critical α-level for pair comparison was set to 0.05. The critical α-level for the cluster test was set to 0.025. The minimum number of elements in the cluster was set to 2, and the number of permutations was 2000. The analysis was carried out using the Fieldtrip package for Matlab.

3. RESULTS

We analyzed the effect of ambiguity of the previous stimulus separately for the current LA and HA stimuli. We examined and compared RT subjects in four conditions. Fig. 1 demonstrates how RT differs under these conditions for the HA and LA stimuli. Multivariate analysis of variance revealed a significant effect of the experimental condition for both stimuli HA: $F(3.57) = 10.787, p < 0.001$; and LA: $F(3.57) = 6.067, p = 0.001$.

For HA stimuli, we observed a minimal reaction time in condition 4, where the two previous stimuli also had a high level of ambiguity. On the contrary, the subjects demonstrated the maximum reaction time in condition 1, where the two previous cubes had a low level of ambiguity. Post hoc analysis using the Wilcoxon test showed that the reaction time in condition 4 (M= 1.01 c, SD= 0.27 c) was significantly lower compared to condition 1 (M= 1.18 c, SD= 0.32 c): $Z = 3.547, p < 0.001$. The analysis of paired differences (Fig. 1, b) showed that 19/20 of the subjects showed an effect in the same direction as the group, and only one subject had an effect in the opposite direction. The reaction time in condition 4 was also lower than in condition 2 (M= 1.12 s, SD= 0.32 s): $Z = 3.323, p = 0.001$. In this case, 2/20 subjects demonstrated an effect in the opposite direction, and one subject showed no effect. Finally, the reaction time in condition 4 was lower than in condition 3 (M= 1.09 s, SD= 0.33 s): $Z = 2.696, p = 0.007$. The analysis of paired differences showed that 15/20 of the subjects showed an effect in the same direction as the group, 4/20 of the subjects showed an effect in the opposite direction, and one subject showed no effect.

For the LA stimuli, we observed the minimum reaction time in condition 1, where the two previous stimuli also had a low level of ambiguity, and the maximum reaction time in condition 4, where the two previous stimuli had a high level of ambiguity. The Wilcoxon test showed that the reaction time in condition 1 (M= 0.82 s, SD= 0.23 s) was significantly lower compared to condition 4 (M= 0.89 s, SD= 0.26 s): $Z = 3.061, p = 0.002$. The analysis of paired differences showed that 18/20 of the subjects showed an effect in the same direction as the group. One subject demonstrated an effect in the opposite direction, and the other - none. The reaction time in condition 1 was also lower than the reaction time in condition 3 (M= 0.89 s, SD= 0.25 s): $Z = 2.13, p = 0.009$. In this case, 4/20 of the subjects showed an effect in the opposite direction. Finally, the reaction time in condition 1 was lower than the reaction time in condition 2 (M= 0.87 s, SD= 0.26 s): $Z = 2.67, p = 0.008$. The analysis of paired differences showed that 4/20 of the subjects had an effect in the opposite direction.

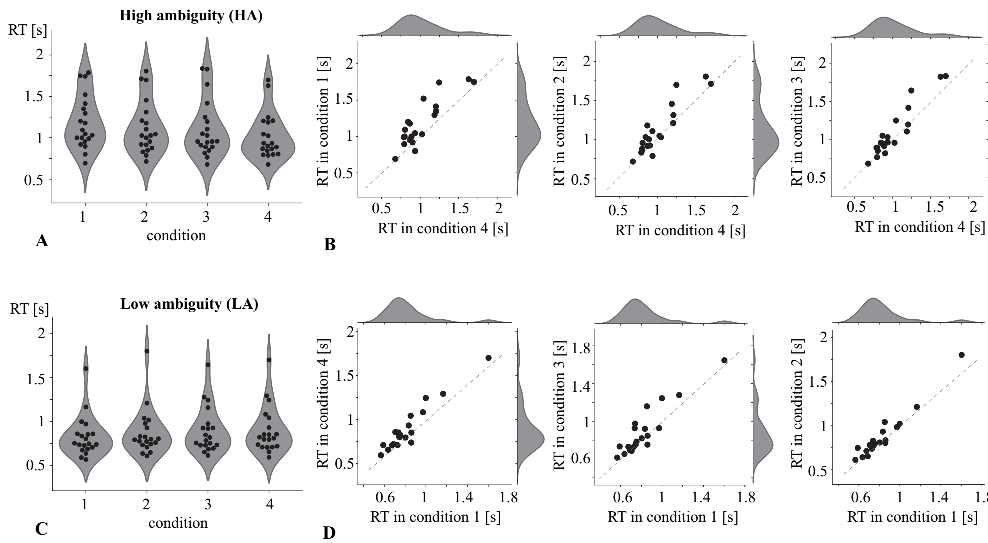

Figure 1. a – RT under four conditions for the current HA stimulus; b – paired differences between RT under different conditions for the current stimulus HA; c – reaction time (RT) under four conditions for the current LA stimulus; d – paired differences between RT under different conditions for the current LA stimulus

Finally, ANOVA with the Greenhouse-Geisser correction showed that the median presentation time of the Necker cube did not change significantly depending on the conditions for both the LA stimuli: $F(1.3, 24.9) = 2.883, p = 0.093$, and for the HA stimuli: $F(1.38, 26.3) = 1.646, p = 0.214$. The ratio between the number of left- and right-oriented current stimuli also did not change in the conditions for both LA stimuli: $F(1.26, 29) = 3.604, p = 0.059$, and for HA stimuli: $F(1.9, 45.5) = 1.159, p = 0.323$. These results indicate that neither the time points at which the subjects were shown visual stimuli nor the orientation of the cube affect the reaction time in the conditions under consideration 1-4. This parameter is affected only by the ambiguity of previous visual stimuli.

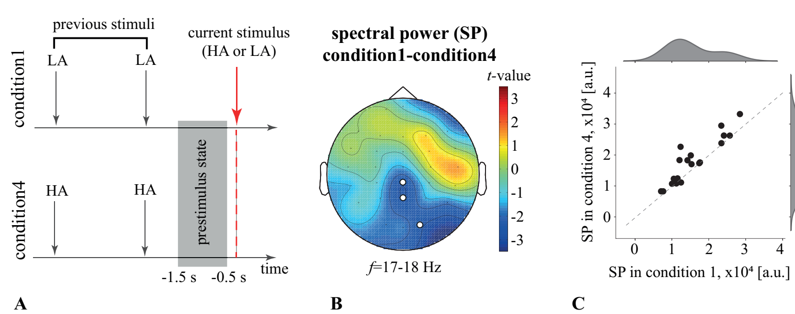

Figure 2. Comparison of prestimulus spectral power (SP) in condition 1 – condition 4 a – schematic representation of experimental conditions; b – the value of t reflects the result of comparing SP between condition 1 and condition 4. The circles show a significant cluster ($p < 0.05$ using the t-criterion for paired samples with cluster correction for multiple comparisons); c – the distribution of paired differences reflects the change in SP between condition 1 and condition 4 for all participants

According to the results described above, the ambiguity of the previous stimulus affected the time the subject spent identifying the current stimuli. RT was lower if the ambiguity level of the previous visual stimulus coincided with the ambiguity level of the current stimulus. This effect was stronger if two previously presented stimuli had the same level of ambiguity (both LA or both HA). We assumed that the brain's processing of previous stimuli affects the prestimul state. So, after processing the LA stimuli (condition 1), it was more favorable for processing the current LA stimulus. In contrast, the prestimul state after processing the HA stimuli was more favorable for processing the current HA stimulus. Accordingly, we compared the spectral power of the prestimulus state between condition 1 and condition 4 (Fig. 2, a).

Comparing prestimulus states formed after processing HA and LA stimuli, we found a significant negative cluster ($p = 0.0475$) in the frequency range of $16 - 18.75$ Hz, localized in the occipital (Oz) and parietal (Pz and CPz) regions of the brain (Fig. 2, b). The spectral power of this cluster in condition 4 (M= 1.7×10^4, SD=7.2×10^4) was higher than in condition 1 (M= 1.5×10^4, SD=6.2×10^4). The analysis of paired differences showed that 17/20 of the subjects showed an effect in the same direction as the group (Fig. 2, c).

4. CONCLUSION

In this paper, the influence of the ambiguity of the previous stimulus on the processing of the current one was analyzed. At the behavioral level, it was found that subjects respond faster to HA stimuli following HA stimuli. At the same time, a faster response to LA stimuli follows LA stimuli. During the EEG analysis, a cluster in a prestimulus state was found, correlating with the influence of previous visual stimuli on the processing of the current visual stimulus. At the same time, there were no significant differences between the conditions either in the time of presentation of the current Necker cube or in the ratio of orientations of the current visual stimuli. Thus, we conclude that the observed change in spectral power was caused only by the ambiguity of the previous stimulus, but not by the duration of the experiment or the current orientation of the stimulus. The detected EEG-marker can be further used in the brain-computer interfaces for attention analysis and error control of the operator performing routine operations involving visual information processing and responses to the repeatedly presented similar sensory stimuli.[23,24]

ACKNOWLEDGMENTS

V.M. was supported by the Russian Science Foundation (project No 20-72-00036) in formulating research hypotheses and designing experimental paradigms. A.K. was supported by President Grant (NSh-589.2022.1.2) in part of data analysis.

REFERENCES

[1] Khramova, M. V., Kuc, A. K., Maksimenko, V. A., Frolov, N. S., Grubov, V. V., Kurkin, S. A., Pisarchik, A. N., Shusharina, N. N., Fedorov, A. A., and Hramov, A. E., "Monitoring the cortical activity of children and adults during cognitive task completion," *Sensors* **21**(18), 6021 (2021).

[2] Chholak, P., Pisarchik, A. N., Kurkin, S. A., Maksimenko, V. A., and Hramov, A. E., "Phase-amplitude coupling between mu-and gamma-waves to carry motor commands," in [*2019 3rd School on Dynamics of Complex Networks and their Application in Intellectual Robotics (DCNAIR)*], 39–45, IEEE (2019).

[3] Kurkin, S., Hramov, A., Chholak, P., and Pisarchik, A., "Localizing oscillatory sources in a brain by meg data during cognitive activity," in [*2020 4th International Conference on Computational Intelligence and Networks (CINE)*], 1–4, IEEE (2020).

[4] Kurkin, S., Badarin, A., Grubov, V., Maksimenko, V., and Hramov, A., "The oxygen saturation in the primary motor cortex during a single hand movement: functional near-infrared spectroscopy (fnirs) study," *The European Physical Journal Plus* **136**(5), 1–9 (2021).

[5] Kurkin, S., Chholak, P., Maksimenko, V., and Pisarchik, A., "Machine learning approaches for classification of imaginary movement type by meg data for neurorehabilitation," in [*2019 3rd School on Dynamics of Complex Networks and their Application in Intellectual Robotics (DCNAIR)*], 106–108, IEEE (2019).

[6] Kurkin, S., Pitsik, E., and Frolov, N., "Artificial intelligence systems for classifying eeg responses to imaginary and real movements of operators," in [*Saratov Fall Meeting 2018: Computations and Data Analysis: from Nanoscale Tools to Brain Functions*], **11067**, 1106709, International Society for Optics and Photonics (2019).

[7] Pavlov, A. N., Pitsik, E. N., Frolov, N. S., Badarin, A., Pavlova, O. N., and Hramov, A. E., "Age-related distinctions in eeg signals during execution of motor tasks characterized in terms of long-range correlations," *Sensors* **20**(20), 5843 (2020).

[8] Maksimenko, V., Khorev, V., Grubov, V., Badarin, A., and Hramov, A. E., "Neural activity during maintaining a body balance," in [*Saratov Fall Meeting 2019: Computations and Data Analysis: from Nanoscale Tools to Brain Functions*], **11459**, 1145903, International Society for Optics and Photonics (2020).

[9] Hramov, A. E., Grubov, V. V., Frolov, N. S., Pitsik, E. N., and Khramova, M. V., "Network structure of children's brain activity during cognitive load," in [*Saratov Fall Meeting 2019: Computations and Data Analysis: from Nanoscale Tools to Brain Functions*], **11459**, 1145909, International Society for Optics and Photonics (2020).

[10] Chholak, P., Kurkin, S. A., Hramov, A. E., and Pisarchik, A. N., "Event-related coherence in visual cortex and brain noise: An meg study," *Applied Sciences* **11**(1), 375 (2021).

[11] Rauss, K. and Pourtois, G., "What is bottom-up and what is top-down in predictive coding?," *Frontiers in psychology* **4**, 276 (2013).

[12] Kok, P., Failing, M. F., and de Lange, F. P., "Prior expectations evoke stimulus templates in the primary visual cortex," *Journal of cognitive neuroscience* **26**(7), 1546–1554 (2014).

[13] Kok, P., Mostert, P., and De Lange, F. P., "Prior expectations induce prestimulus sensory templates," *Proceedings of the National Academy of Sciences* **114**(39), 10473–10478 (2017).

[14] Teufel, C., Dakin, S. C., and Fletcher, P. C., "Prior object-knowledge sharpens properties of early visual feature-detectors," *Scientific reports* **8**(1), 1–12 (2018).

[15] Wacongne, C., Labyt, E., van Wassenhove, V., Bekinschtein, T., Naccache, L., and Dehaene, S., "Evidence for a hierarchy of predictions and prediction errors in human cortex," *Proceedings of the National Academy of Sciences* **108**(51), 20754–20759 (2011).

[16] Henson, R. and Rugg, M., "Neural response suppression, haemodynamic repetition effects, and behavioural priming," *Neuropsychologia* **41**(3), 263–270 (2003).

[17] Vogels, R., "Sources of adaptation of inferior temporal cortical responses," *Cortex* **80**, 185–195 (2016).

[18] Gilbert, C. D. and Li, W., "Top-down influences on visual processing," *Nature Reviews Neuroscience* **14**(5), 350–363 (2013).

[19] Badarin, A. A., Skazkina, V. V., and Grubov, V. V., "Studying of human's mental state during visual information processing with combined eeg and fnirs," in [*Saratov Fall Meeting 2019: Computations and Data Analysis: from Nanoscale Tools to Brain Functions*], **11459**, 114590D, International Society for Optics and Photonics (2020).

[20] Maksimenko, V., Kuc, A., Frolov, N., Kurkin, S., and Hramov, A., "Effect of repetition on the behavioral and neuronal responses to ambiguous necker cube images," *Scientific Reports* **11**(1), 1–13 (2021).

[21] Grubov, V. V., Badarin, A. A., Frolov, N. S., and Pitsik, E. N., "Analysis of real and imaginary motor activity with combined eeg and fnirs," in [*Saratov Fall Meeting 2019: Computations and Data Analysis: from Nanoscale Tools to Brain Functions*], **11459**, 114590B, International Society for Optics and Photonics (2020).

[22] Hramov, A. E., Koronovskii, A. A., Makarov, V. A., Pavlov, A. N., and Sitnikova, E., [*Wavelets in neuroscience*], Springer (2015).

[23] Grigorev, N., Savosenkov, A., Lukoyanov, M., Udoratina, A., Shusharina, N., Kaplan, A., Hramov, A., Kazantsev, V., and Gordleeva, S., "A bci-based vibrotactile neurofeedback training improves motor cortical excitability during motor imagery," *bioRxiv* (2021).

[24] Pavlov, A., Pitsik, E., Guyo, G., Frolov, N., Grubov, V., Pavlova, O., Wang, Z., and Hramov, A., "Effects of healthy aging on electrical activity of the brain during motor tasks characterized with wavelets," *The European Physical Journal Plus* **136**(4), 1–11 (2021).