HUMAN, TECHNOLOGIES AND QUALITY OF EDUCATION, 2023
https://doi.org/10.22364/htqe.2023.42

EXPLORATION OF EEG MARKERS OF SENSORIMOTOR FUNCTIONING DURING INCORRECT VERSUS CORRECT DECISIONS

Aleksandrs Kolesovs[1], Klavs Evelis[1], Liga Ozolina-Molla[1], Liga Plakane[1], Juris Porozovs[1], Viktors Veliks[1]

[1] University of Latvia, Latvia

ABSTRACT

Open-skill sports are demanding for athletes' decision-making. Incorrect decisions can have substantial consequences. Complex programs for elite athletes include improvement of their neurocognitive functioning. Simultaneously, making errors remains underrepresented in broader sports science. The present study explored EEG markers of sensorimotor reactions under incorrect versus correct responses to visual stimuli.

Seven male participants (24.2±2.5 years) completed the Choice Response Time task (CRT) with simultaneous EEG registration. Two color stimuli (red and green) and a discriminative stimulus (black) were presented on an LCD screen, using PSYCHOTOOLBOX coded CRT task. Stimulus and response events were synchronized with EEG amplifier NVX-136, and 32 channels of EEG were recorded. Data were preprocessed in EEGLAB, and event-related potential (ERP) calculations were performed in ERPLAB. ERP was analyzed for correct and incorrect color choices and reactions to the discriminative stimulus. The electrodes represented the visual (O1, Oz, O2), frontal (F3, Fz, F4), and sensorimotor (C3, Cz, C4) cortex.

Behavior data revealed a shorter reaction time during the incorrect decision (4.6% of cases) than during the correct one, 398.1±55 ms vs. 456.8±96 ms. In the N2 peak area, the incorrect color stage differed significantly from the two correct stages (e.g., the amplitude of -1.624 mkV at a latency of 264 ms for the correct color stage and -1.779 mkV at a latency of 254 ms for the correct discriminating stage vs. -3.716 mkV at a latency of 300 ms for the incorrect color stage for channel F3, peak N2).

Correct decision stages had similar ERP wave peak patterns. Incorrect decisions deviate from functioning during correct ones. Differences in the N2 peak area represented conflict in decision-making during incorrect decisions. Simultaneously, the shorter latency of a motor reaction requires investigating the role of decision-making conflicts in impulse control and behavioral consequences.

Keywords: *electroencephalography, errors, event-related potential, reaction time, sensorimotor functioning.*

Introduction

Incorrect decisions have substantial consequences in different domains of human activities (Kim et al., 2022; Pooladvand & Hasanzadeh, 2022; von Bechtolsheim et al., 2022). Sports presents a kind of activity oriented to maximal results under competitive conditions. These conditions associate with time pressure and are highly demanding for athletes' attentional processes and decision-making, especially in open-skills sports (Memmert, 2009; Wang, 2016). For elite athletes, complex training programs include specific components that improve their neurocognitive functioning, shortening reaction time and reducing errors (Larson et al., 2012; Niederer et al., 2016; Tang & Posner, 2009). Simultaneously, the effects of programs remain limited in amplitude and generalizability to other kinds of activity (Kolesovs et al., 2020; Larson et al., 2012; Tang & Posner, 2009). Moreover, sensorimotor functioning while making errors remains underrepresented in a broader scientific discourse, including sports science.

The dominating discourse of empirical studies indicates a tendency to focus on correct rather than incorrect functioning. For example, a *Google Scholar* search (April 27, 2023) presents about 321,000 items for "event-related potential" and only about 690 items for "error-related potential." Our research team emphasizes that errors and incorrect decisions are highly significant because of their consequences and require particular focus in investigation. Therefore, the present study aimed to explore EEG markers of sensorimotor reactions under correct versus incorrect responses to visual stimuli.

Objective data form a solid base for the development of any field of science. Therefore, we have focused on brain functioning and revealing brain activity as highly topical for modern psychology (e.g., Jeste & Lee, 2019). Electroencephalography (EEG) is among the methods of identification of neural correlates of human perception, decision-making, and action. Event-related potential presents a way to identify dynamics of perceptive and decision-associated arousal. Simultaneously, reaction time measures allow us to characterize the motor component of the sensorimotor cycle (e.g., Reigal et al., 2019). In order to compare functioning under correct and incorrect decisions and explore in greater detail their neuro correlates, our exploratory study focused on EEG markers of sensorimotor reactions under incorrect versus correct responses to visual stimuli.

Our special attention focused on the N200/P300 complex of brain responses because of their modulation by conflict-provoking tasks (Enriquez-Geppert et al., 2010). Following Enriquez-Geppert et al. (2010), we have selected the "go/nogo" task paradigm for assessing correct and incorrect responses. This paradigm encompasses processes of discriminating between stimuli, making decisions, and initiating or inhibiting motor action within a relatively simple procedure (e.g., pressing the buttons under exposure to certain stimuli and not pressing them under exposure to a specific discriminative stimulus). It allows the application of the "go/nogo" paradigm in general and clinical populations (Lamp et al., 2022; Wang et al., 2020).

Simultaneously, we have maintained a broader temporal focus of investigation, addressing differences between correct and incorrect responses in the interval after the decision was made. It should be noted that extending the time interval links observed activity to memory processes (Megías et al., 2021; Voss & Paller, 2008). This extension requires a better differentiation of conscious and more automatic processes (Kane et al., 2000). However, it was out of the focus of our study, aimed at the analysis of a broader temporal range of correct and incorrect responses.

Accounting for brain functional asymmetry, we have expected to identify some differences in the functioning of the right and left hemispheres potentially associated with the leading and non-leading hand (Serrien & Spape, 2009; Zhavoronkova et al., 2019). Aiming to better interpret the results of our exploratory study, we have added control over participants' handedness by including right-handed participants only.

Method

The study was conducted in the scientific cooperation frame and involved the analysis of existing data. Data were collected in November – December 2022 under the project, supported by the Latvian Council of Science under Fundamental and Applied Research grant No. lzp-2019/1-0152.

Participants

Participants of the exploratory study were seven right-handed male emerging adults (24.1 ± 2.4 years). For this exploratory study, inclusion criteria were male gender, age 18 to 29, regular physical exercises (from regular exercising two to three times per week to competitive athletes), and voluntary participation. The age range was limited because of age-related variability of reaction time (Adleman et al., 2016). The exclusion criteria were color blindness, acute upper extremities or back injury, and any sign of infectious disease (accounting for pandemic limitations in 2022).

Measures

Choice Response Time task (CRT) with simultaneous EEG registration was performed to assess functioning under correct and incorrect reactions. Within the PSYCHOTOOLBOX coded CRT task, two color stimuli (red and green) for choice by right and left hands and a discriminative stimulus (black) for non-reacting were presented on an LCD screen (see Figure 1). As a result, the "go/nogo" task paradigm was applied to investigate correct and incorrect responses.

Stimulus and response events were synchronized with EEG amplifier NVX-136, and 32 channels of EEG were recorded. Accounting for the exploratory nature of the study, the following electrodes were selected for region of interest (ROI): visual cortex O1, Oz, O2, frontal cortex F3, Fz, F4, parietal cortex P3, Pz, P4, and sensorimotor cortex C3, Cz, C4.

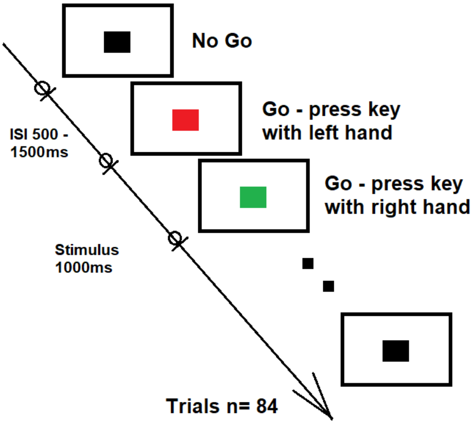

Figure 1 Schematic representation of the Choice Response Time task

Procedure

EEG was recorded with a sample rate of 1000 Hz and cut-off frequencies of 0.1–100 Hz with impedances < 5 kΩ, which included the 32 standard electrodes of the 10–20 system and A1 and A2 electrodes as reference channels. NVX-136 recording system with application software (NVX136, Medical Computer Systems Ltd.) was used.

EEG recordings were preprocessed and analyzed using Matlab (The MathWorks, Inc.) based EEG analysis software products, EEGLAB (http://sccn.ucsd.edu/eeglab), applying some custom processing scripts. The EEG was re-referenced to the computed average reference. 50 Hz noise in EEG signals was rejected using bandpass filters with 48–52 Hz values. Then, EEG signals with performance errors or remaining artifacts exceeding ± 100 µV in any channel and eye-blinked artifacts were rejected using the ICA procedure (based on online EEGLAB tutorial http://sccn.ucsd.edu/wiki/Chapter_09:_Decomposing_Data_Using_ICA) from data before processing. Additionally, EEG trials were inspected visually before event-related potentials (ERP) calculation using the ERPLAB plugin. Within ERP, the following reactions were analyzed: correctly and incorrectly pressed buttons during color choice, correct reaction on the discriminative stimulus (no button pressed), and incorrect reaction on discriminating stimulus (button pressed). The level of significance of 0.05 was maintained for statistical comparisons. Higher levels of significance are additionally reported in the Results section.

Results

Reaction time was the main indicator representing behavior data for correct and incorrect reactions to stimuli. The analysis shows that reaction time during the incorrect decision (4.6% of cases) was shorter than during the correct decision, 398.1 ± 55 ms vs. 456.8 ± 96 ms, respectively.

Simultaneously, we have observed statistically significant differences in P300 peak areas between all experimental stages ($p < 0.01$). In the N200 peak area, the incorrect color stage differed significantly from the two correct stages. Both correct decisions (i.e., correct reactions on the color stimuli and no reactions when black stimuli were presented) show similar ERP waves, especially at F3, Fz, C4, O1, Oz, and O4 electrode positions (Figure 2).

For example, the amplitude of –1.624 mkV at a latency of 264 ms for the correct color stage for channel F3 (Figure 2), and peak N200 was similar to the amplitude of –1.779 mkV at a latency of 254 ms for the correct discriminating stage. Simultaneously, both correct stages differed from the incorrect color stage with the amplitude of –3.716 mkV at a latency of 300 ms.

Significant alterations were observed at sensorimotor ROI electrodes (Figure 2). A spike at 114 ms with an amplitude of 1.95 mkV was observed at C4 when participants made an error (pressed the wrong keys) on the color stimulus. It can be related to stimulus recognition in the visual cortex. The spike (P100) was common in the right hemisphere electrodes O2, P4, and C4 in cases of incorrect color stimulus reactions.

P300 spike in the right hemisphere had greater amplitude, except for frontal cortex ROI electrodes. These differences between hemispheres were in parietal and sensorimotor ROI ($p < 0.05$), which is valid for all observation cases.

Post-stimulus time intervals were over 500 ms in parietal ROI, also having a greater amplitude in the case of an error in color choice than during correct decisions. A similar pattern was observed in visual cortex ROI with two spikes at 450 ms and 670 ms.

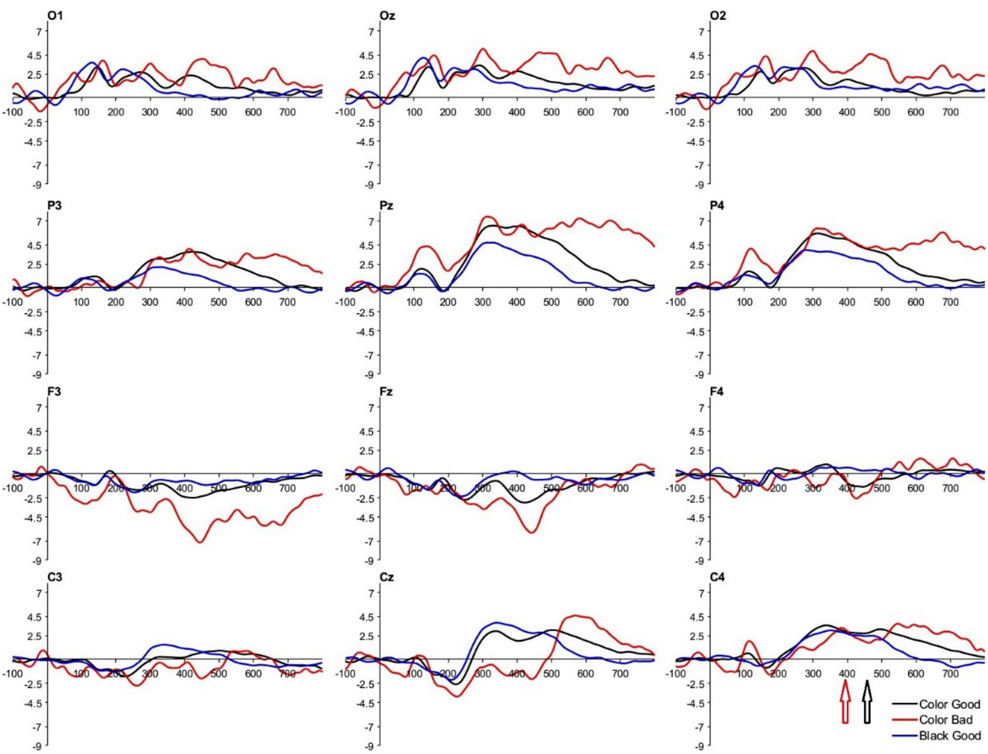

Figure 2 Time amplitude of ERP in visual (O), parietal (P), frontal (F), and motor (C) cortex (arrows in C4 indicate motor reaction time for correct and incorrect decisions)

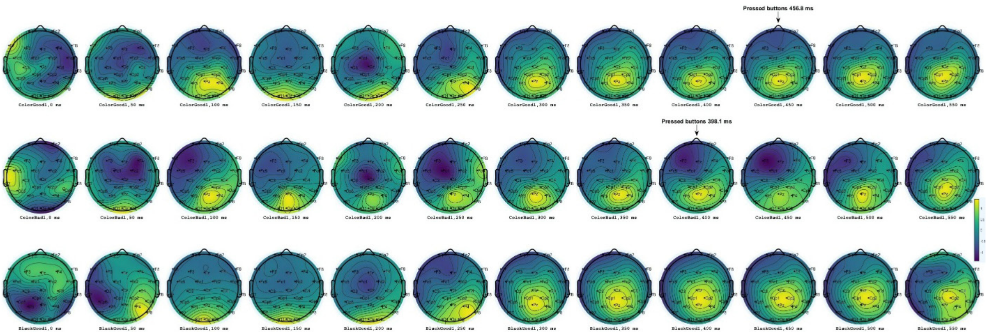

Figure 3 Topographic EEG map of activation patterns for correct (1st and 3rd line) and incorrect (2nd line) decisions and reactions in the interval from 0 to 550 ms after stimulus onset

Post-stimulus time intervals were over 500 ms in parietal ROI, also having a greater amplitude in the case of an error in color choice than during correct decisions. A similar pattern was observed in visual cortex ROI with two spikes at 450 ms and 670 ms.

The topographic map (Figure 3) also presented similarities in regions' activation patterns for both correct decision stages from 150 to 500 ms after stimulus onset. The map indicated similar activation of regions during correct behavioral outcome (correctly pressed and not pressed button). Black (no reaction) color perception has different patterns at the time 50 ms to 150 ms.

At P300, we have observed similar activation patterns in all correct case conditions. Simultaneously, activation of frontal ROI during correct and incorrect reactions visibly contrasted in the 400 to 500 ms interval.

Discussion

Both correct decision stages had similar ERP wave peak patterns in amplitude and time dimensions. From the perspective of the "go/nogo" task paradigm (e.g., Enriquez-Geppert et al., 2010), this similarity points to more minor differences between correct initiation or inhibition of motor action than between correct and incorrect initiation of this action.

It should be noted that incorrect decision events were rare, but current exploration revealed their significant deviance from functioning during correct decisions. Accounting for differences in the N200 peak area in the frontal cortex, they can represent higher conflict in decision-making during incorrect decisions. It concurs with previous findings on the role of conflict in frontal cortex activation (Enriquez-Geppert et al., 2010).

The similarity in brain activation patterns on P300 in all correct reaction cases suggests that common cognitive loading processes take place. Simultaneously, we have observed low amplitude in the right frontal cortex, which probably relates to the following error key pressing in the next time slot – 398 ms. Kane et al. (2000) suggest that such observed patterns may relate to conscious or automatic behavior. Additional studies are required to differentiate these modes of action.

Simultaneously, the latency of a motor reaction was shorter for incorrect decisions than for correct ones. It indirectly supports the findings of Bechtolsheim et al. (2022) on the negative association between faster motor action and its quality. It also indicates a need for further investigation of the role of decision-making conflicts (Enriquez-Geppert et al., 2010) in impulse control during sensorimotor reactions. In addition, including a broader time interval can help understand the neurocognitive consequences of errors.

As expected, we have identified differences associated with sensorimotor asymmetry in brain functioning. Higher motor activation in the right hemisphere than in the left hemisphere (C4 vs. C3 ROI electrodes) indicated higher arousal associated with the involvement of the left hand. Since our participants were right-handed, higher amplitudes may indicate the involvement of additional resources to manage the movements of the non-leading hand under challenging tasks (Zhavoronkova et al., 2019; Serrien & Spape, 2009).

The post-stimulus (400–800 ms) behavior differed in the error case in comparison with both correct cases. Relevant activation of frontal ROI can point to additional involvement of working memory in processing information regarding the outcomes of a particular decision and action (Megías et al., 2021). Therefore, investigation of working memory processes in relation to incorrect decisions should be considered as an option for further consideration.

A limited number of respondents form the main limitation for identifying error-related potentials during the analysis of the EEG procedure. However, seven participants provided data for exploratory insights into the problem. In addition, the present study was also limited in the variability of tasks challenging the correct performance. It resulted in a relatively low number of incorrect reactions. Especially, incorrect reactions on a discriminant stimulus were rare. It points to difficulties exploring inhibitory processes within the "go/nogo" paradigm. Another paradigm in studying these processes can be combined and contrasted with the current approach.

One more limitation of our study is associated with a relatively broad temporal interval for reacting to each stimulus. Accounting for the significant association between time pressure and errors (Pooladvand & Hasanzadeh, 2022; von Bechtolsheim et al., 2022), temporal frame and time-related characteristics of stimuli form a set of independent variables for further studies. However, an extension of temporal intervals can involve memory processes as a challenge for parallel investigation (Megías et al., 2021; Voss & Paller, 2008), while their shortening of the interval can limit the investigation of error monitoring processes and consequences of errors (Wang et al., 2020). Therefore, exploring chains of errors and correct decisions form an additional topic for empirical studies. Moreover, focusing on physical activity requires a combination of physical load and assessment of neurocognitive functioning. It will provide more relevant information for dealing with errors in sports.

Our findings point to the possible applied value of the study. Preliminary analysis indicates a significant challenge for practitioners aimed at developing precious reactions and stable behavioral patterns in the field of sports (Larson et al., 2012; Wang, 2016) or other disciplines (Kim et al., 2022; Pooladvand & Hasanzadeh, 2022; von Bechtolsheim et al., 2022). The initial differentiation and decision-making require no less attention than focusing on completing or not completing the activity. Therefore, a special focus on early reactions to visual stimuli is needed in training programs.

Conclusions

The exploratory study revealed that incorrect decisions are associated with shorter motor reaction time and higher loading in various regions of interest. These findings confirm a need for investigation of the role of decision-making conflicts in impulse control and its behavioral consequences. Extending the time interval for depicting consequences is significant. Simultaneously, shortening time intervals between stimuli can form a frame for studying chains of reactions. More complex cognitive tasks can provide a broader spectrum of links between correct and incorrect decisions and actions.

Funding details

Data collection for this exploratory study was supported by the Latvian Council of Science under Fundamental and Applied Research grant No. lzp-2019/1-0152.

REFERENCES

Adleman, N. E., Chen, G., Reynolds, R. C., Frackman, A., Razdan, V., Weissmann, D. H., Pine, D. S., & Leibenluft, E. (2016). Age-related differences in the neural correlates of trial-to-trial variations of reaction time. *Developmental Cognitive Neuroscience, 19*, 248–257. https://doi.org/10.1016/j.dcn.2016.05.001

Enriquez-Geppert, S., Konrad, C., Pantev, C., & Huster, R. J. (2010). Conflict and inhibition differentially affect the N200/P300 complex in a combined go/nogo and stop-signal task. *NeuroImage, 51*(2), 877–887. https://doi.org/10.1016/j.neuroimage.2010.02.043

Jeste, D.V., & Lee E.E. (2019). The emerging empirical science of wisdom: Definition, measurement, neurobiology, longevity, and interventions. *Harvard Review of Psychiatry 27*(3), 127–140. https://doi.org/10.1097/HRP.0000000000000205

Kane, K.A., Picton, T.W., Moscovitch, M., & Winocur, G. (2000). Event-related potentials during conscious and automatic memory retrieval. *Cognitive Brain Research, 10*(1–2), 19–35. https://doi.org/10.1016/S0926-6410(00)00018-5

Kim, J., Yu, M., & Hyun, S.S. (2022). Study on factors that influence human errors: Focused on cabin crew. *International Journal of Environmental Research and Public Health, 19*(9), 5696. MDPI AG. https://doi.org/10.3390/ijerph19095696

Kolesovs, A., Salkovs, D., & Blinovs, A. (2020). Developing and measuring attention in boxers: Mixed coaches' expertise and reaction time measures. *Society. Integration. Education. Proceedings of the International Scientific Conference*, *7*. https://doi.org/10.17770/sie2020vol7.4937

Lamp, G., Sola Molina, R.M., Hugrass, L., Beaton, R., Crewther, D., & Crewther, S.G. (2022). Kinematic studies of the go/no-go task as a dynamic sensorimotor inhibition task for assessment of motor and executive function in stroke patients: An exploratory study in a neurotypical sample. *Brain Sciences,12*(11), 1581. https://doi.org/10.3390/brainsci12111581

Larson, N. C., Sherlin, L., Talley, C., & Gervais, M. (2012). Integrative approach to high-performance evaluation and training: Illustrative data of a professional boxer. *Journal of Neurotherapy, 16*, 285–292. https://doi.org/10.1080/10874208.2012.729473

Megías M., Ortells, J.J., Carmona, I., Noguera, C., & Kiefer, M. (2021). Individual differences in working memory capacity modulate electrophysiological correlates of semantic negative priming from single words. *Frontiers in Behavioral Neuroscience, 15*(765290). https://doi.org/10.3389/fnbeh.2021.765290

Memmert, D. (2009). Pay attention! A review of visual attentional expertise in sport. *International Review of Sport and Exercise Psychology, 2*, 119–138. https://doi.org/10.1080/17509840802641372

Niederer, D., Plaumann, U., Seitz, T., Wallner, F., Wilke, J., Engeroff, T., Giesche, F.,

Pooladvand, S., & Hasanzadeh, S. (2022). Neurophysiological evaluation of workers' decision dynamics under time pressure and increased mental demand. *Automation in Construction, 141*, 104437. https://doi.org/10.1016/J.AUTCON.2022.104437

Reigal, R. E., Barrero, S., Martín, I., Morales-Sánchez, V., de Mier, R. J.-R., & Hernández-Mendo, A. (2019). Relationships between reaction time, selective attention, physical activity, and physical fitness in children. *Frontiers in Psychology, 10*, e02278. https://doi.org/10.3389/fpsyg.2019.02278

Serrien, D. J., & Spape, M.M. (2009). The role of hand dominance and sensorimotor congruence in voluntary movement. *Experimental Brain Research, 199,* 195–200. https://doi.org/10.1007/s00221-009-1998-8

Tang, Y. Y., & Posner, M. I. (2009). Attention training and attention state training. *Trends in Cognitive Sciences, 13*, 222–227. https://doi.org/10.1016/j.tics.2009.01.009

Vogt, L., & Banzer, W. (2019). How does a 4-week motor-cognitive training affect choice reaction, dynamic balance and cognitive performance ability? A randomized controlled trial in well-trained, young, healthy participants. *SAGE Open Medicine, 7*, 1–8. https://doi.org/10.1177/2050312119870020

von Bechtolsheim, F., Schmidt, S., Abel, S., Schneider, A., Wekenborg, M., Bodenstedt, S., Speidel, S., Weitz, J., Oehme, F., & Distler, M. (2022). Does speed equal quality? Time pressure impairs minimally invasive surgical skills in a prospective crossover trial. *International Journal of Surgery, 104*, 106813. https://doi.org/10.1016/J.IJSU.2022.106813

Wang, J. (2016). Key principles of open motor-skill training for peak performance. *Journal of Physical Education, Recreation & Dance, 87*(8), 8–15. https://doi.org/10.1080/07303084.2016.1216341

Wang, L., Gu, Y., Zhao, G., & Chen, A. (2020). Error-related negativity and error awareness in a Go/No-go task. *Scientifc Reports, 10*(1), 4026. https://doi.org/10.1038/s41598-020-60693-0

Voss, J.L., & Paller, K.A. (2008). Neural substrates of remembering: Electroencephalographic studies. In H. Eichenbaum (Ed.), *Memory Systems: A Comprehensive Reference*, *3*, (pp. 79–98), *Learning and Memory: A Comprehensive Reference*, in 4 vols. (J. Byrne, Ed.). Oxford: Elsevier Press.

Zhavoronkova, L., Moraresku, S., Boldyreva, G., Sharova, E., Kuptsova, S., Smirnov, A., Masherov, E., Maksakova, O., & Pronin, I. (2019). FMRI and EEG reactions to hand motor tasks in patients with mild traumatic brain injury: Left-hemispheric sensitivity to trauma. *Journal of Behavioral and Brain Science, 9*, 273–287. https://doi.org/10.4236/jbbs.2019.96020