ORIGINAL ARTICLE

UDC: 612.85
DOI: https://doi.org/10.2298/VSP210902033S

Sensorimotor rhythm neurofeedback training and auditory perception

Neurofeedback trening senzomotornog ritma i auditivna percepcija

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Abstract

Background/Aim. In everyday communication, people are exposed to a myriad of sounds that need to be sorted and relevant information extracted. The ability of a person to concentrate on certain sounds in a noisy background environment, perform selective attention, and focus their auditory attention is crucial for everyday functioning and communication. The aim of this study was to investigate the effect of the sensorimotor rhythm (SMR) (12–15 Hz) neurofeedback (NFB) training to improve auditory cognition measured by the achievements in the Quick speech-in-noise (QuickSIN) test, changes in the amplitudes and latencies of components of auditory evoked potentials (AEP) N100, N200, and P300 in the auditory oddball discrimination task, and changes in the spectral power of the SMR. **Methods.** The study included 16 healthy participants aged 25–40 years (8 males and 8 females). Each participant had 20 daily sessions of SMR NFB training. Auditory cognitive functions and electrophysiological correlates of cognitive processing were recorded 5 times – before NFB, after 5, 10, and 20 sessions, and one month after the last session of NFB. **Results.** The results showed a statistically significant decrease in N200 and P300 latencies at frontal midline (Fz), central midline (Cz), and parietal midline (Pz) regions, an improvement on the QuickSIN test, and an increase in electroencephalogram SMR rhythm spectral power in the Cz region as a result of the NFB SMR training. No significant effect of the NFB training on the N100, N200, and P300 amplitudes on Fz, Cz, and Pz was found. **Conclusion.** The obtained results suggest that SMR NFB affects auditory perception in terms of shorter latencies of AEP and better performance on the QuickSIN test.

Key words:
auditory perception; cognition; electroencephalography; event-related potentials, p300; evoked potentials, auditory; feedback, sensory.

Apstrakt

Uvod/Cilj. U svakodnevnoj komunikaciji, ljudi su izloženi mnoštvu zvukova koje treba razvrstati i iz kojih treba izvući bitne informacije. Sposobnost osobe da se koncentriše na određene zvukove u bučnom okruženju, da selektivno i usredsređeno usmerava sluh je ključna za svakodnevno funkcionisanje i komunikaciju. Cilj studije bio je da se ispita efekat *neurofeedback* (NFB) treninga senzorimotornog ritma (SMR) (12-15 Hz) na auditivnu percepciju koji se meri rezultatima postignutim na *Quick speech-in-noise* (QuickSIN) testu, promenama amplituda i latenci komponenti auditivnih evociranih potencijala (AEP) N100, N200 i P300 tokom zadatka auditivne diskriminacije i promenama spektralne snage SMR talasa. **Metode.** U studiju je bilo uključeno 16 zdravih ispitanika uzrasta od 25 do 40 godina (8 muškog i 8 ženskog pola). Svaki ispitanik imao je 20 svakodnevnih SMR NFB treninga. Auditivne kognitivne funkcije i elektrofiziološke korelacije kognitivnih procesa snimane su 5 puta, i to pre primene NFB treninga, posle 5, 10, i 20 treninga i jedan mesec nakon poslednjeg treninga. **Rezultati.** Rezultati su pokazali statistički značajno smanjenje latenci N200 i P300 komponenti u regijama *frontal midline* (Fz), *central midline* (Cz) i *parietal midline* (Pz), bolje postignuće na QuickSIN testu kao i povećanje spektralne snage elektroencefalografije SMR ritma u Cz regiji kao rezultat NFB SMR treninga. Nije utvrđen statistički značajan efekat NFB treninga na N100, N200 i P300 amplitude u Fz, Cz i Pz regijama, niti na spektralnu snagu SMR talasa. **Zaključak.** Dobijeni rezultati ukazuju na potencijalni efekat SMR NFB treninga na poboljšanje procesa auditivne diskriminacije u smislu kraćih latenci komponenti AEP i boljeg postignuća na QuickSIN testu.

Ključne reči:
percepcija, auditivna; saznanje; elektroencefalografija; potencijali povezani sa događajima, p300; evocirani potencijali, auditivni; povratna informacija, senzorna.

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Introduction

In everyday communication, people are exposed to a myriad of sounds that need to be sorted and relevant information extracted. The term "cocktail party effect" was first used by Cherry in 1953, which refers to focusing on one sound, often speech, while at the same time suppressing other unwanted sounds in a noisy background [1]. The cocktail party effect is an example of selective attention and illustrates the phenomenon of being able to focus auditory attention on a particular stimulus while filtering out a range of other stimuli [2]. The ability to concentrate on certain sounds in a multi-sound environment is crucial for daily functioning and communication.

The P300 event-related potential (ERP) can be considered a neurophysiological marker of auditory attention. P300 is an endogenous cognitive neuroelectric phenomenon that occurs under the influence of endogenous stimuli; it depends on the state of vigilance, concentration, and type of task the subject is required to perform. The ERP components are represented by a series of positive and negative waves (N100, P100, N200, P200, and P300) of different duration and amplitudes, the most significant of which is the P300.

Different treatments using different sub-disciplines of biomedical engineering are used to improve cognitive functions and thus improve the quality of life. Cognitive training with neurofeedback (NFB), as a form of operative conditioning, is being increasingly used in a healthy population with the aim of increasing performance. The use of NFB dates back to early experiments conducted by Kamiia in the 1960s and Sterman in the 1970s, in which epileptic cats were trained to improve sensorimotor rhythm (SMR) of the brain, leading to less frequent epileptic seizures [3]. NFB, a form of biofeedback, is a therapeutic method based on monitoring the electroencephalogram (EEG) and providing feedback on the brain activity of subjects, which can be learned to regulate via operative conditioning [4].

Using real-time NFB protocols allows the acquisition of control of localized brain activity. NFB allows the experimenter to noninvasively manipulate brain activity as an independent variable leading to specific behavioral changes [5].

SMR waves training refers to cognitive function, better focus, and increased attention and concentration [6]. SMR waves (12–15 Hz) are beta waves that occur in the sensorimotor region of the brain regulated by the thalamocortical loop [7]. With the NFB SMR training, the subject trains to gain control in terms of increasing the amplitude of the SMR wave, resulting in increased attention and better focus. Literature data indicate that normal healthy individuals can learn to control and modify the components of their EEG activity and thus contribute to improving cognitive function.

The aim of this study was to investigate the effect of NFB SMR (12–15 Hz) training on auditory cognition measured by the following: the achievement of hearing speech in a noisy background, the Quick speech-in-noise (QuickSIN) test, changes in the amplitudes and latencies of event-related potentials (N100, N200, P300) in the auditory oddball discrimination task, and changes in the spectral power of the SMR in healthy participants aged 25 to 40 years.

Methods

Participants

The study involved 16 healthy participants of both sexes (8 males and 8 females), 25 to 40 years old. The participants were recruited from the Institute for Experimental Phonetics and Speech Pathology and the Life Activities Advancement Center in Belgrade, Serbia, whose Laboratory for cognitive research conducted the experiments. The participants were without hearing or speech disorders, with no prior or current neurological or psychiatric illnesses (based on the participant's verbal report). All participants were right-handed, according to the Edinburgh Handedness Inventory. Each participant gave their written informed consent before the experimental procedure. This study was approved by the local Ethics Committee (No. 22/19 from February 18, 2019) according to the Declaration of Helsinki.

Auditory event-related potentials recording

The auditory event-related potentials (aERPs) were recorded using a Nihon Kohden Electroencephalograph (model EEG-4314F) and Neuroscan Acquire 4.0 software. To obtain the P300, an auditory "oddball" paradigm with two tones was used, with 80% non-target and 20% target stimuli. The participants had a task to react by pressing a control button with the right hand's thumb each time they heard a tone that differed from the other mostly presented tones. A total of 80% of each presented tone had a frequency of 1,000 Hz, and 20% of tones were oddballs with a frequency of 2,000 Hz. The tones were randomly presented to the participants. The participants listened to the tones using earphones. Three Ag/Ag-Cl ring electrodes for aERPs registration were positioned according to the 10–20 International system for electrode placement at the frontal midline (Fz), central midline (Cz), and parietal midline (Pz) regions. The reference electrode was set to the ear lobes, and the ground electrode was on the forehead. The impedance was kept below 5kΩ with no more than 1kΩ difference between electrodes. The software has its own implemented tool for artifact rejection. Each recording section with more than 20% of rejected trials due to excessive artifacts was discarded and redone. Each participant underwent the experimental procedure in the morning hours (9–11 am). For each participant, averaged amplitude (μV) and latency (ms) of N100, N200, and P300 waves were obtained for each electrode (Fz, Cz, and Pz). The aERPs were recorded at the beginning (t1), after 5 (t2), 10 (t3), and 20 (t4) NFB SMR treatments, as well as one month after the last NFB SMR treatment (t5).

EEG recording and analysis

EEG signal recording was performed on an EEG device Nihon Kohden (EEG – 1200K Neurofax) with a fixed cap

(Electrocap, model number 16755, International, Inc.) with Ag/AgCl surface electrodes filled with electro-conductive gel, which provides 19 EEG channels. The electrodes are positioned according to the 10/20 International Electrode Positioning System. During the experiment, participants were placed in a sitting position in a soundproof room. The task was to keep their eyes open and reduce movement as much as possible. EEG was recorded for 3 min during the "resting state" with no ongoing task. The participants were placed in a square-shaped cube made of white non-transparent curtains in order to eliminate visual stimuli that may have influenced the experimental tasks. The recording was done approximately around noon (12 am +/- 1 h). The EEG data were transposed into EEGLAB Software for Independent Component Analysis (ICA)-dependent artifact rejection. All artifacts, including body movement, eye blinks, eye movements, teeth clenching, or ECG artifacts, were removed from the EEG trace. From the 3 min resting state, we have selected six 10-s artifact-free periods: two segments from the first, second, and third minute of the recording. Those segments were averaged for each participant in further analysis.

We used a fast Fourier transform (FFT) to separate SMR rhythm (12–15Hz). Before computing FFT, each epoch was multiplied by an appropriate windowing function (Hanning window) in order to avoid border problems (leakage). Spectral power was calculated using in-house written MATLAB script (MathWorks, version 7) and EEGLAB software packages. For topographic spectral maps plotted in EEGLAB, we used all 19 electrodes.

QuickSIN test

The QuickSIN test is from the Hearing In Noise Tes group of methods that uses test sentences mixed with defined doses of interfering noise. The attention of the respondents is crucial for the success of this test. With this method of measurement, speech communication in noisy environments is simulated. The starting hypothesis for measuring speech intelligibility in the presence of noise is that a person with normal hearing understands 50% of words if the signal/noise (S/N) ratio is 2 dB. The QuickSIN test uses sentences dosed with a certain level of noise of the "cocktail-party" type. The smallest test unit is a list with six test sentences. Each test sentence contains five key words (30 key words for one list). The level of interfering noise added to "clean" sentences depends on the position of the test sentence in the list. Sentences are played through speakers or headphones, and the respondent tries to recognize the key words. A comparison is made between what was heard and what was actually reproduced. For the needs of the QuickSIN method, 126 test sentences and 21 test lists were formed ($21 \times 6 = 126$) [8]. Due to the different levels of distracting noise in test sentences, not all sentences are of the same weight for perception. As the level of interfering noise increases, the intelligibility of key words decreases. The most difficult case is with the sixth test sentence, where the level of speech and disturbing noise is the same. For this sentence, it is predicted that a person with normal hearing will correctly perceive one or two key words. If the respondent loses concentration on these sentences for a moment, he/she may not perceive any key words.

Neurofeedback SMR protocol training

The NFB SMR training was performed using BioTrace software for Nexus – 10B2015. The electrode was set to a Cz region (central midline – vertex region). The experimental task for participants was to perform an NFB SMR training by increasing the amplitude of SMR rhythm (12–15Hz). During the trials, the participant looks at the physiological responses on the screen in the form of pictures and video games. The information that comes from this process is feedback, which is reflected via changes in the image or sound of the video game used for training. The games are designed to let the participant advance in the game if he or she can bring the physiological function that is being rehearsed to the desired level. Each participant participated in 20 sessions of NFB SMR protocol training, three times a week for 28 min of effective recording: 2 min of resting state period (watching a blank computer screen) at the beginning, 4 training trials, each lasting 6 min, and 2 min of resting state at the end.

After 5 (t2), 10 (t3), and 20 (t4) NFB SMR training sessions, as well as one month after the last session (t5), participants were re-registered with aERPs using the same procedure as at the beginning.

Statistical analyses

The sample size is small, and the data were with non-normal distribution. Hence, the comparisons of NFB SMR power, amplitudes and latencies of aERPs before and after NFB SMR training, and EEG SMR spectral power values were analyzed using nonparametric statistics – Kruskal-Wallis test for exploring the effect of time point (before NFB, after 5, 10, 20 sessions, and one month after the last training session) and Wilcoxon signed-rank test for post hoc multiple comparisons reporting Z score and *p*-value. The results of the QuickSIN test were tested using one-way ANOVA with the time point factor followed by Student's *t*-test. In each comparison, a 95% confidence interval was used.

Results

NFB SMR power

First, we analyzed the resting state NFB SMR power after 5, 10, and 20 NFB SMR training sessions (Figure 1). The Kruskal-Wallis test found a significant effect of session number on NFB SMR power in the Cz electrode location: $H(47) = 3.478$, $p = 0.03$. Post hoc Mann-Whitney *U* test found a statistically significant difference between NFB SMR power between the 5th and 10th session: $Z = 2.327$, $p = 0.02$, 10th and 20th session: $Z = 1.965$, $p = 0.049$, as well as 5th and 20th session: $Z = 2.612$, $p = 0.009$. The results showed a statistically significant linear increase in SMR power in the Cz region due to the application of the NFB SMR training protocol.

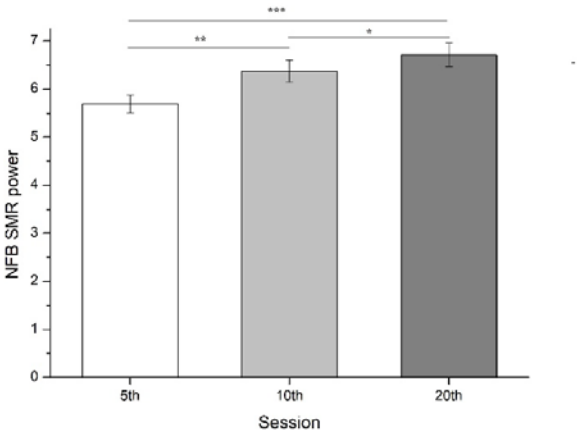

Fig. 1 – Average neurofeedback (NFB) sensorimotor rhythm (SMR) power measured in the central midline (Cz) region after 5, 10, and 20 NFB SMR training protocols; * $p < 0.05$; ** $p < 0.02$; *** $p < 0.01$, based on the Mann-Whitney *U* test.

Auditory event-related potentials

The second task was to probe the effect of NFB SMR training protocol on aERPs amplitude and latency changes.

Using the Kruskal-Wallis test, we found no overall statistically significant effect of time point (number of NFB SMR training sessions) on aERP amplitudes of N100, N200, and P300. However, there is a trend of amplitude increase of the N100 wave when time point t1 (before NFB SMR training) is compared to time points t4 (after 20 NFB SMR training sessions) and t5 (one month after the 20th training session). In addition, for the P300 wave, there is a statistically significant difference for the Cz electrode location between t1 and t5 ($Z = 2.327$, $p = 0.002$) with an almost statistically significant linear increase of amplitude in time (Figure 2).

The Kruskal-Wallis test found a statistically significant effect of time point (number of NFB SMR training sessions) on aERPs latency of N200: $H(79) = 2.965$, $p = 0.018$, and P300: $H(79) = 3.889$, $p = 0.002$ (Figure 3).

However, the post hoc Mann-Whitney *U* test found that the Cz electrode location had a linear decrease in latency for both N200 and P300 waves. For N200 wave, the following differences were present: t1 > t2: $Z = 2.272$, $p = 0.023$; t1 > t3: $Z = 2.330$, $p = 0.02$; t1 > t4: $Z = 2.430$, $p = 0.015$; t1 > t5: $Z = 2.992$, $p = 0.01$. For P300 wave, the following differences were present: t1 > t2: $Z = 2.561$, $p = 0.01$; t1 > t3: $Z = 2.755$, $p = 0.006$; t1 > t4: $Z = 3.517$, $p = 0.001$; t1 > t5: $Z = 3.362$, $p = 0.001$.

QuickSIN test

The obtained results showed a linear increase from t1 to t4 (Figure 4). The one-way ANOVA found a statistically significant effect of time point on the score: $F(5, 1675) =$

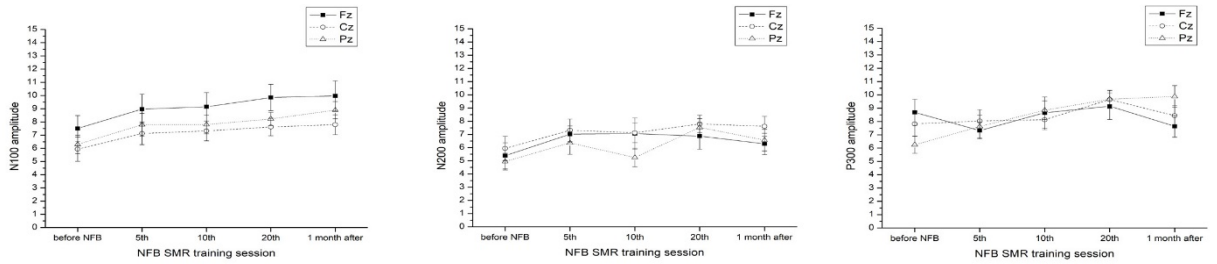

Fig. 2 – Average amplitude value (μV) of N100 (left panel), N200 (middle panel), and P300 (right panel) waves at frontal midline (Fz), central midline – vertex (Cz), and parietal midline (Pz) electrode location at five time points: before neurofeedback (NFB) sensorimotor rhythm (SMR) training and after 5, 10, and 20 sessions, as well as one month after the last session.

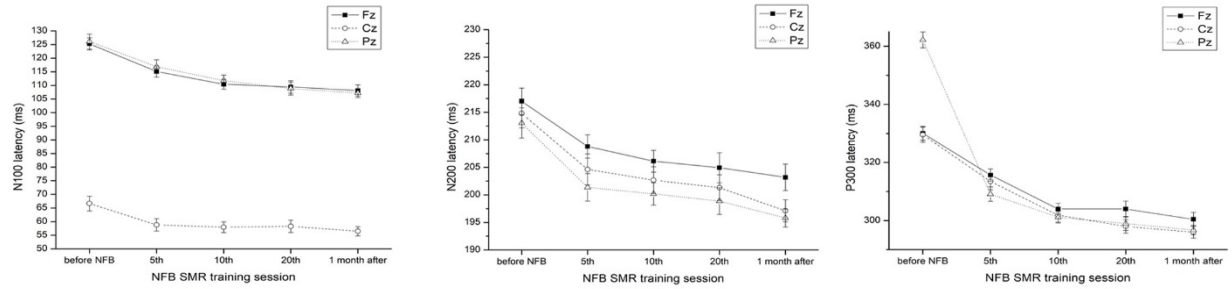

Fig. 3 – Average auditory event-related potentials latency value (ms) of N100 (left panel), N200 (middle panel), and P300 (right panel) waves measured in frontal midline (Fz), central midline – vertex (Cz), and parietal midline (Pz) electrode location at five time points: before neurofeedback (NFB) sensorimotor rhythm (SMR) training protocol and after 5, 10, and 20 sessions, as well as one month after the last session.

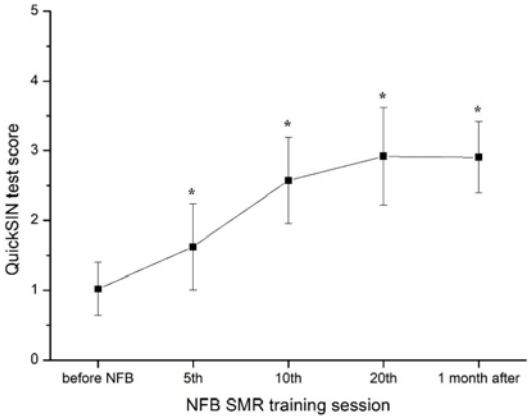

Fig. 4 – The result of the Quick speech-in-noise (QuickSIN) test. The average number of perceived key words in the sixth test sentence, where the level of speech and disturbing noise is the same; *statistically significant difference in test score compared to t1 – before neurofeedback (NFB) sensorimotor rhythm (SMR) training.

5.248, $p < 0.01$. The post hoc Bonferroni correction found a difference between t1 and t2, t2 and t3, t1 and t3, t1 and t4, as well as t1 and t5. No differences were found between t3 and t4, nor between t4 and t5. The obtained results showed a better achievement on the QuickSIN test as a result of the NFB SMR training protocol.

EEG SMR spectral power

The final level of analysis was to probe the effect of NFB SMR training protocol on EEG SMR rhythm spectral power. The Kruskal-Wallis test found a significant effect of time points on the SMR spectral power in the Cz region: H(80) = 3.895, $p = 0.009$. Post hoc Mann-Whitney *U* test showed that this effect was driven by the increase in SMR spectral power after training sessions compared to the initial t1 period (before NFB training). After 20 NFB SMR training sessions (t4), there was an increase in SMR spectral power over the entire sensorimotor region (C3, Cz, and C4 electrode location) (Figure 5). An interesting result was that even one month after the last NFB SMR training, there was still an increase in the Cz region.

Discussion

This study explored the effect of NFB SMR training on auditory cognition measured by the achievement on the QuickSIN test, changes in the amplitudes and latencies of aERPs recorded at Fz, Cz, and Pz regions during standard auditory oddball discrimination task, and changes in the spectral power of the SMR measured by EEG.

An effect of NFB SMR training was found for aERP latencies. NBF SMR training caused a decrease in latencies of auditory ERP N200 and P300 waves. However, no differences in amplitudes were found (although there is a trend of increase in amplitude as a result of NFB SMR training). To generate the potential of P300, the oddball paradigm was used. It is the acoustic discrimination test, which uses two types of tone: high-frequency arrhythmic tone and low-frequency rhythmic tone. The difference between the two tones is in frequency and intensity [9]. The respondent is presented with two types of auditory stimuli – the first one being "rare" or "unexpected" arrhythmic tone, which represents the target stimulus and occurs in random order and differs in frequency from the second "standard" or "expected" tone. The participant is required to respond to the "unexpected" tone (by pressing a key) and ignore the "standard" tone, i.e., to recognize target stimuli in a series of stimuli that differ in their characteristics (volume, duration) and are less likely than the standard ones. The oddball experimental paradigm requires the attention and concentration of the respondents.

ERP waveforms are quantitatively described by amplitude level, latency length, and topographic distribution. The amplitude reflects the magnitude of neural activity and typically ranges from 1 to 30mV [10]. Latency represents the time interval, i.e., the period from the moment of stimulation, to the appearance of maximum amplitude, i.e., the peak of ERP, and ranges from several hundred ms.

Latency reflects the speed of processing sensory stimuli as a consequence of distinction from the other stimuli. Therefore, shorter latencies are considered to reflect more effective mental performance compared to longer latencies. In a study by Kober et al. [11] on healthy young adults after NFB SMR training, the experimental and not the control group showed an increase in the amplitudes of N100 and P300. We found a similar result regarding a sample of healthy individuals. In a study by Reichert et al. [12], an in-

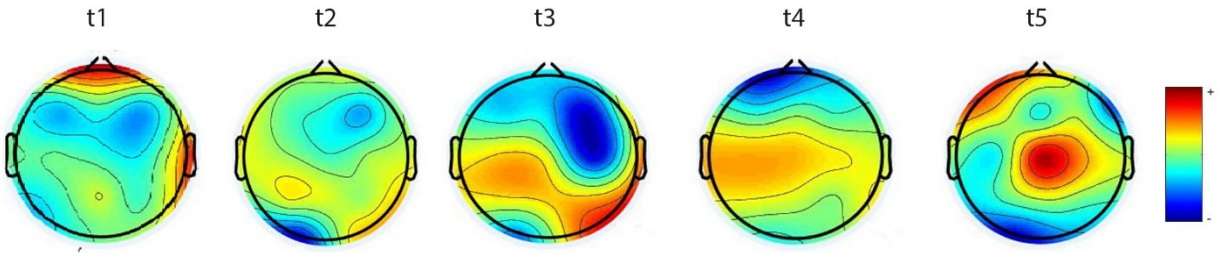

Fig. 5 – Averaged electroencephalogram sensorimotor rhythm (12–15Hz) spectral power [10 x log10 (μV2/Hz)] scalp distribution. t1 – before neurofeedback sensorimotor rhythm training protocol; t2 – after 5 training sessions; t3 – after 10 training sessions; t4 – after 20 training sessions; t5 – one month after the last training session.

crease in N100 and P300 amplitude was observed in a post-stroke patient in an experimental group who had SMR training, whereas the control group showed no difference. This finding is partially in line with our study, which found a trend of amplitude increase of N100 wave when time point t1 is compared to time points t4 and t5. In addition, for the P300 wave, there is a statistically significant difference in the Cz electrode location between t1 and t5. The earliest wave in the sequence arises about 100 ms from stimulation and is designated as wave N100 due to the negative polarization. The negative wave (the N200 component) occurs 200 ms from stimulation and is associated with the process of sensory discrimination. The role of N200 is mainly focused on "cognitive controls," a concept that encompasses monitoring and control of motor responses [13].

The P300 wave has the longest latency and the highest amplitude registered above the central and parietal regions of the cerebral cortex. The time span of this P300 component by Coles and Rugg [14] can range from 250 ms to 900 ms, with an amplitude ranging from at least 5 μV to the usual limit of 20 μV. It is an endogenous response to an unknown task, i.e., response to target stimuli [15]. Extension of the P300 latency, which reflects the time of assessment and categorization of stimuli, indicates a slowdown in mental functions. The lack of attention causes a decrease in the P300 amplitude or the absence of a P300 wave.

A large number of studies of NFB training in a healthy population show that the SMR protocol is an effective method to improve cognitive performance in terms of increasing working memory, improving attention and perceptual ability, and reducing the time of reaction [16–21].

Several studies by different authors have shown that the latency and/or amplitude values of P300 in normal adults are reproducible and stable without statistically significant differences in retesting state at different time intervals [22–25]. That is in line with our finding that P300 latency is stable even one month after the last training, which might point to a plastic change in the brain's electric activity that can last for a longer period of time. In assessing the short-term and long-term effects of beta EEG-NFB in healthy subjects, Engelbregt et al. [26] found that frontal beta activity increased after 15 sessions of NFB and that these effects remained stable for at least 3 years. Regarding the changes in EEG, patients showed reduced strength of SMR after treatment, while NFB aimed to increase this frequency range. The observed effects in the EEG were specific for the narrow SMR frequency range of 12–15 Hz and were not found in the alpha and beta frequency bands, suggesting that the effects were specific for the frequency range. This finding suggests that NFB SMR leads to control over certain EEG frequencies but does not structurally regulate this EEG activity [27].

In our study, we found an opposite result – an increase in EEG SMR spectral power as a result of NFB SMR training. Gadea et al. [28] showed in their study that healthy women were able to improve SMR rhythm after one training session with NFB, which was positively associated with performance improvement in the Dichotic Listening test that measures executive attention. NFB SMR training effects have been reported through the increment of the SMR on improvements in auditory attention and phonological awareness [29, 30].

All respondents in the study had a better performance on the QuickSIN test with a linear trend of increasing the achievement from the beginning even to the one month after the last NFB SMR training session. The brain circuit of SMR has a thalami-cortical origin. It is a bottom-up mechanism that reduces the interference of somatosensory information [11]. This inhibition, as a result of an increase in SMR, may lead to better integration of information processing in the cerebral cortex. Hence, the NFB SMR training might act within the inhibitory mechanism of the thalamic circuitry [17, 31].

This finding indicates the potential usefulness of NFB SMR training as an operative conditioning paradigm by the SMR protocol of neuromodulatory therapy in improving auditory cognition. In addition to our study, other studies found that the standard NFB SMR training protocol in healthy individuals might be an efficient method for improving attention and perceptive abilities and reducing reaction times and errors by commission [16].

Conclusion

The limitation of our study was the small sample size. Hence, the generalization of the obtained results should be made with caution. In addition, the effect of NFB SMR training on other attention modalities (visual, for instance) was not assessed. That might be interesting and important for future research. However, the achieved long-lasting enhancement of selective auditory attention using NFB SMR training in our study might be a promising field of research towards its application not only in healthy individuals but also in neurotherapy in children with specific developmental disorders that affect auditory attention (hearing impairment, attention deficits, language disorders, etc.) as well as adults with neurological and/or cognitive impairments.

Conflict of interest

The authors declare no conflict of interest.

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Received on September 2, 2021
Revised on March 12, 2022
Accepted on March 14, 2022
Online First March 2022