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Abstract

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Keywords

reaction time, normoxia, hypoxia, EEG-biofeedback

Authors

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Article

The effect of 6-week EEG-biofeedback training in normobaric hypoxia and normoxia conditions on reaction time in elite judo athletes

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Abstract: Introduction: The purpose of this study was to evaluate the effect of Biofeedback Training in normoxic and normobaric hypoxic conditions on reaction times in judo athletes. Material and methods: The participants in the experimental group underwent thetha/beta1 training under simulated hypoxic conditions in a laboratory equipped with a normobaric hypoxia generation system (LOS-HYP1/3NU, Lowoxygen Systems, Germany), at a simulated altitude of 2500m above sea level (FiO_2 = 15.5%). Each cycle of the study consisted of 15 training sessions. The training sessions lasted for 20 minutes, with 4 sets of 4 minutes each and a 1-minute break in between. In the initial phase, participants underwent EEG biofeedback training every other day. The control group followed the same frequency and duration of EEG biofeedback training sessions as the experimental group and demonstrated an identical pattern, but under normoxia conditions. Results: The results indicated significant differences in Theta/Beta ratio values after the 5th, 11th, and 15th training sessions between the hypoxia and normoxia groups. Moreover, theta/beta1 protocol in normobaric hypoxic conditions statistically significantly improved their complex reaction times after each training cycle compared to the control group in normoxia conditions. Conclusions: The findings indicate that neurofeedback training in normobaric hypoxia conditions may considerably enhance reaction skills, particularly complex reactions, in a sports context.

Keywords: reaction time, normoxia, hypoxia, EEG-biofeedback.

1. Introduction

Reaction time plays a crucial role in many sports disciplines, which is why shaping and developing this ability is a priority in the training process. During a judo match, athletes exhibit the capacity to rapidly analyze situations, anticipate their opponent's movements, and make prompt decisions based on their opponent's actions. Due to the fast pace of the match, speed is a decisive factor in the fight. It can be divided into three components: reaction time (simple and complex), speed of a single movement, and the frequency of movements [1–4].

The essence of reaction time training is usually exemplified by exercises that require multiple responses to stimuli. Depending on the type of reaction – simple or complex – and the type of stimulus (visual, sensory, auditory or mixed), tasks vary in terms of the type and intensity of the stimulus and the way in which it is responded to (e.g. exposure to several different stimuli with the need to respond to only one of them, or making different responses to individual stimuli). Many researchers dealing with the issue of reaction time and its importance in sport point out that it can only be improved to a limited extent, as it largely depends on individual neural characteristics and muscular systems [5]. However, there are also opposing opinions. For example, Ando et al. [6] demonstrated that reaction time can be improved. Sixteen students underwent EEG-Biofeedback (EEG-BF) training and their reaction times to visual stimuli improved after a three-week protocol [6]. Moreover, the data shows a continued increase in reaction time in athletes. For instance, the reaction times of sprinters at the 2008 Olympics were superior to those of the 2000 and 2004 Olympics [7].

Existing scientific findings indicate that intensive training improving visuomotor coordination results in a reduction of simple reaction time [8], but there is a lack of scientific reports regarding the training of complex reaction time. The absence of effective methods for developing the mentioned motor characteristic encourages a search for new, innovative solutions. One of them may be the application of EEG-BF training performed under normoxic and normobaric hypoxic conditions in the training of athletes.

The EEG-BF method aims to control and modify the bioelectrical activity of the brain through training, based on the assumption that this activity reflects the emotional states of the individual being studied [9]. Assuming that specific frequencies of individual brain waves may correspond to specific emotional states, based on the EEG recording, we can determine the current arousal level of the person under study. This allows for the planning of appropriate training, involving the modification of the frequencies of selected brain waves (inhibiting or enhancing them within specific ranges) so that the athlete can master the ability to appropriately stimulate or inhibit the bioelectrical activity of the brain, responsible for achieving a state of optimal concentration and readiness to accomplish a specific research goal [10].

Neurofeedback is a technique that aids individuals in consciously regulating their brain waves [10]. Specifically, EEG is measured during neurofeedback sessions. The EEG's different components are then extracted and provided to subjects through an online feedback loop in the form of audio, video, or a combination thereof. The fundamental concept underlying neurofeedback training is that individuals can learn how to regulate their bioelectrical brain processes, as measured by the EEG, through operant conditioning. Electrodes are fixed to the scalp, and real-time extraction of specific parameters including slow cortical potentials, alpha rhythm, sensorimotor rhythm (SMR), and theta/beta ratio (TBR) occurs from the signal [15].

Neurofeedback treatment protocols predominantly target the treatment of alpha, beta, delta, theta, and gamma waves, either individually or in combination, such as the alpha/theta ratio or theta/beta ratio [11,12]. The alpha, beta, theta, and TBR are widely implemented protocols. A stronger decline in cognitive control after stress induction was correlated with a higher baseline of TBR [13]. TBR demonstrates high test-retest reliability and predicts attentional control scores over one week [14]. All things considered, TBR is probably a stable electrophysiological marker of executive control. Moreover, TBR is a marker of cognitive processing capacity that has been proven to correlate with P300 latency [15].

TBR is the ratio of activity in the theta band (4–7 Hz) to activity in the beta band (13–30 Hz) and has been connected to various aspects of cognitive control and motivated decision-making [16–18], attentional control in healthy young adults [13, 14, 19, 20], off-task thoughts, and reversal learning [21, 22].

In the context of these findings, the biofeedback method seems to be interesting in supporting the process of shaping concentration, influencing the speed of stimulus processing, and the effectiveness of athletes' performance. Training with the use of biofeedback appears to be a modern, effective training tool, especially where athletes are seeking increasingly innovative solutions. It is important to remember that the key factor determining effective stimulation of neuronal mechanisms is the appropriate selection of both the research protocol and the stimulation time, as well as the application of appropriate training stimuli.

It has been documented that physical exercise and cognitive training have beneficial effects on cognition [23, 24], but less is known about the potential impact on cognition adaptations after cognitive training in different environmental conditions such as normobaric hypoxia.

Thus, this study aimed to assess the impact of normoxic and normobaric hypoxic conditions on improving reaction times in judo athletes, as well as to broaden the existing knowledge regarding the effectiveness of EEG-BF training application in elite sports.

2. Material and methods

2.1. Participants

The study included 24 male elite judo athletes. Each athlete was a member of the Polish National Team and held either an International Master Class (MM) or National Master Class (M) – purposive selection. All subjects had recent medical examinations confirming their ability to perform intense physical exertion.

The subjects were randomly divided into an experimental group (H-group; n = 12; age 19.6 ±1.4 years; height 182.2 ±5.1 cm; body weight 78.6 ±7.9 kg; percent body fat, %FAT 10.1 ±5.7%) in normobaric hypoxia EEG-BF training or a control group (N-group; n = 12; age 20.1 ±1.6 years; body height 182.1 ±4.5 cm; body weight 74.1 ±6.1 kg; %FAT 8.8 ±1.7%) in normoxia EEG-BF training.

Before participation in the study, all subjects were informed of the purpose of the study, and they gave written consent to participate. Participants were also informed that they could withdraw from further participation in the experiment at any time without giving a reason. The research project was conducted under grants NRSA303953 and NRSA404054 and approved by the Bioethics Committee for Scientific Research at the Academy of Physical Education in Katowice. The research was conducted at the Human Psychomotor Laboratory and Hypoxia Laboratory of the Jerzy Kukuczka Academy of Physical Education in Katowice.

2.2. The general procedures

The research was carried out over four cycles that differed in the frequency of EEG biofeedback sessions for both the control and experimental groups. The experimental group underwent training under simulated hypoxic conditions in a laboratory fitted with a normobaric hypoxia generation system (LOS-HYP1/3NU, Lowoxygen Systems, Germany). The training sessions for the experimental group were conducted at a simulated altitude of 2500m above sea level (FiO_2 = 15.5%). Each cycle of the study consisted of 15 training sessions. The training sessions lasted for 20 minutes, comprising 4 sets of 4 minutes each with a 1-minute break in between. During the initial phase, the participants underwent EEG biofeedback training every other day. In the subsequent phase, the frequency remained the same as before, but the training was conducted under normobaric hypoxic conditions. Following this, the frequency of sessions increased, with the third cycle involving daily training under normoxic conditions, and the fourth cycle under hypoxic conditions. The experimental group underwent theta/beta training as a fundamental protocol to enhance concentration and achieve the athletes' narrow attention in normobaric hypoxia conditions. The control group's study followed the same frequency, and duration of EEG biofeedback training sessions, and demonstrated an identical pattern to that of the experimental group, but in normoxia conditions. The preparation process was identical for both groups.

2.3. *EEG-BF training*

Biofeedback training was conducted through the use of the EEG DigiTrack software, which was fitted with the ExG-32 head. The device quality was verified through the acquisition of an ISO certificate and a CE medical certificate. Before EEG recording, the impedance levels of the electrodes as well as the inter-electrode were checked using the built-in impedance sensor on each occasion. The requirement for commencing diagnosis and EEG biofeedback training was an impedance level below 5 kΩ and an inter-electrode measurement differing by no more than 1 kΩ. During diagnosis, the reference electrode was positioned on the left earlobe, the ground electrode on the right earlobe, and the active electrode at point Cz, following the international 10–20 system [25]. Throughout the assessment, the EEG signal was recorded from points C3 and C4 on the scalp, utilizing an Ag/AgCl electrode (Blue Sensor SP, Ambu). The signals collected from the points facilitated the primary training goal of attaining an optimal balance between the fast (beta) and slow (theta) wave activity. The utilized electrodes were active and arranged using a stretchable Lycra cap, adhering to the 10–20 system. Conductive gel was administered subcutaneously using a blunt needle, while abrasive cream (Nuprep, Weaver, and Company) and alcohol-imbued wipes were employed for electrode site preparation.

The study participants were asked to complete the Mood and Six Emotions Measurement Questionnaire immediately before each task. This questionnaire served for the interpretation of the results by a neurologist, who then decided on the qualification for the training [26]. The participants also performed reaction time tests each time. Subsequently, EEG Biofeedback training was conducted under normoxia or normobaric hypoxia conditions. During each session, participants sat in front of a 17-inch LCD computer monitor at a distance of 70 cm, where an EEG Biofeedback animation was displayed. Participants were instructed to avoid head movements and electrode impedance was continuously monitored. The session commenced after the EEG electrodes were mounted, followed by a 2-minute rest period aimed at acclimating participants to the training situation and recording a non-training sample of EEG signals.

The EEG-BF training involved recording neuronal activity generated by nerve cells in the form of electrical impulses. These impulses, captured by electrodes, were processed by a computer program to obtain amplitude values in specific frequency ranges. Each athlete during EEG-BF training had the same task: to control the image on the monitor so that the car in the animation moved along the road. The car's movement occurred through EEG-BF training when the power of the EEG signal from two C3 and C4 electrodes (according to the international 10–20 system) in the Beta and Theta bands was recorded. When the amplitude of the waves changed in the intended direction, the car moved. The threshold defining the required amplitude value of Beta and Theta waves was presented as a horizontal line on the chart to maintain the threshold above the upper limit of the Beta band amplitude and below the lower limit of the Theta band amplitude during the session, ensuring a relatively constant level of reward for all participants.

The trainee focused on the task appearing on the monitor, receiving feedback on the level of bioelectrical activity from the registered brain region. When the desired pattern of brain bioelectrical frequency was achieved, points were awarded, and recorded by an auditory signal. If unwanted frequency bands dominated, no points were awarded. Brain activity signals were processed to create feedback between visual and auditory observation and the trainee's bioelectrical brain activity reaction. As a result, feedback occurred, allowing the bioelectrical activity of the brain (neuron activity) to change to the expected level. Immediately after the EEG Biofeedback training, reaction time tests from selected Vienna Test System (VTS) trials were conducted.

2.4. Reaction Time Tests

The impact of EEG Biofeedback training on the reaction time of judo athletes was assessed using selected trials from the VTS. The tests were conducted immediately before and right after the EEG Biofeedback training. All trials were repeated twice with a 5-minute interval, considering the better result from the two measurements. Using a reaction time (RT) measurement device, which is a component of the Vienna Test System, the simple reaction to visual stimuli was examined. The participants' task was to move their hand from the 'rest key' and press the 'reaction key' as quickly as possible when the yellow diode lit up. Based on the obtained data, the average reaction time in seconds was calculated. The complex reaction time, on the other hand, was assessed using a decision-making device (DG), where each trial required the rapid pressing of the appropriate key – depending on the color of the illuminated diode – when the stimulus appeared. The program indicated all correct and incorrect reactions, the average reaction time, and the standard deviation of the mean reaction time. The signal appeared 15 times.

2.5. Statistical analysis

To characterize the structure of the examined variables, basic descriptive statistics were calculated in the form of measures of central tendency (the mean) and measures of variability (the standard deviation). Both results and input data were presented as records in a tabular matrix.

The distributions of the examined variables were verified using the Shapiro-Wilk test for normality. The homogeneity of variances was checked with Levene's test. In summary, all variable variances had a normal distribution with slight left or right deviations, which, however, fell within the normal range. Additionally, the significance level for Mauchly's test was checked. Since the results were statistically insignificant, it indicated the sphericity of variances.

To verify the significance of differences between the groups, repeated measures analysis of variance (ANOVA) was applied. In the case of significant differences, further analysis was conducted using the Tukey post-hoc test. The F-statistic and significance levels were presented. For all analyses, a statistical significance level of $p < 0.05$ was adopted. All calculations were performed using the Statistica v.13 software (StatSoft, USA, CA).

3. Results

Figure 1 graphically presents changes in theta/beta ratios (TBR) values after individual EEG-BF training sessions in different environmental conditions in the N and H groups.

What is visually evident (Fig. 1) has been confirmed in the analysis of variance (ANOVA). The results indicated significant differences in TBR values after the 5th, 11th, and 15th training sessions between the H and N groups (Tables 1–2). As evident from Table 2, the result of post-hoc tests for TBR session values significantly differed between the H and N groups.

The conducted analyses of TBR value differences were reflected in the results of simple and complex reaction time tests after all sessions, especially concerning the complex reaction times (Table 3). The analysis revealed that athletes from the experimental (H) group, as a result of implementing the theta/beta1 protocol in normobaric hypoxic conditions, statistically significantly improved their complex reaction times after each training cycle compared to the control (N) group in normoxia conditions. Similar changes were not observed with simple reaction time tests. Athletes in Group H improved their simple reaction time; however, the differences in the improvement in the reaction time in Group N were not at the threshold of statistical significance.

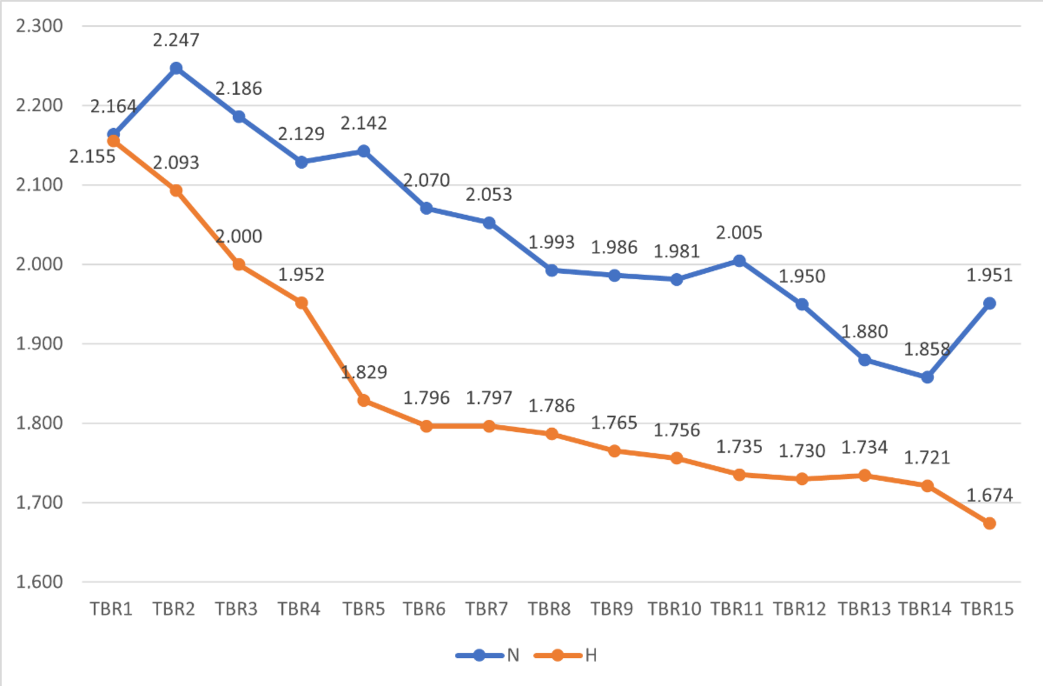

Figure 1. Changes in TBR values after individual sessions in normoxia and hypoxia

Table 1. The result of the analysis of variance ANOVA between groups in terms of TBR values after individual sessions

Intervention	F	p
TBR1	1.775	0.196
TBR2	2.971	0.099
TBR	3.721	0.067
TBR4	2.140	0.158
TBR5	4.821	0.039
TBR6	4.081	0.056
TBR7	3.973	0.059
TBR8	3.144	0.090
TBR9	3.657	0.069
TBR10	3.240	0.086
TBR11	4.727	0.041
TBR12	3.471	0.076
TBR13	1.783	0.195
TBR14	1.598	0.219
TBR15	9.110	0.006

Table 2. The result of post-hoc tests for TBR session values significantly differed between the H and N groups

	TBR 15	
Group	N	H
	Differential means	
	2.142	1.828
N		0.039
H	0.039	
	TBR 15	
Group	N	H
	Differential means	
	2.004	1.735
N		0.041
H	0.041	
	TBR 15	
Group	N	H
	Differential means	
	1.951	1.674
N		0.006
H	0.006	

Table 3: Tukey's post-hoc test for simple and complex reaction time (VST) after 15 sessions of EEG BF sessions in the N and H groups, with $p < 0.05$

Group	H	N
Differential means	0.221 s	0.226 s
simple reaction time H		0.045
simple reaction time N	0.045	
Differential means	0.326 s	0.352 s
complex reaction time H		0.001
complex reaction time N	0.001	

4. Discussion

This study aimed to assess the effect of neurofeedback training on the reaction times of judo athletes in simple and difficult tasks under normoxic and normobaric hypoxic conditions, with a specific focus on Beta and Theta waves. The primary objective was to investigate the correlation between brainwave patterns and response abilities in the context of sports, thus contributing to the existing knowledge in sports psychology. The study found significant differences in Theta/Beta ratio values after the 5th, 11th, and 15th training sessions between the hypoxia and normoxia groups. Additionally, the theta/beta1 protocol in normobaric hypoxic conditions statistically improved complex reaction times after each training cycle compared to the control group in normoxia conditions. The study's findings support previous research in the field, highlighting the importance of psychological training in maintaining optimal focus and responsiveness under high-pressure situations. The study emphasizes the critical role of reaction time in sports, particularly in disciplines like judo, where swift and accurate responses to visual stimuli are crucial for success.

An EEG biofeedback program was developed to manage concentration levels and improve the visual attention of judo athletes, resulting in decreased reaction times. The training aimed to enhance the efficiency of visual processing by focusing on increasing the activity of fast beta waves and decreasing the activity of slow theta waves. Research by Engel and Fries [27] suggests that beta wave frequency is associated with increased visual attention processing, which is crucial for decision-making and reaction planning [28]. Additionally, the authors note that beta activity in the motor cortex is linked to faster motor responses to stimuli. Based on these findings, the current study selected the theta/beta1 training program to improve the visual reaction speed of judo athletes.

The research involved a specific group of athletes, all members of the national team of the Polish Judo Association. Notably, the novelty of the neurofeedback training applied in this study was its implementation under both normoxic and normobaric hypoxic conditions. This approach allowed for diverse measurement situations, facilitating the selection of the most advantageous configuration. The obtained results underwent statistical analysis, enabling a precise evaluation of the training protocols to the reaction times achieved in both research groups after each session.

Athletic achievements result from a comprehensive and carefully designed long-term training regimen, encompassing the athlete's technical-tactical, physical, and mental preparation. For a sports training system to effectively enhance an athlete's performance to its fullest potential, continuous improvements, adjustments, and diversification of tools and training techniques are essential. Numerous athletes and coaches emphasize the significance of the psychological component in an athlete's training regimen, considering it a vital element for success at the highest level [29]. Effective mental preparation has a positive impact on the ability to cope with the pressure of competition, the challenges of training, and the ability to maintain motivation and focus, even in the face of increasing fatigue. Consequently, it contributes to the overall efficiency of training. However, the importance of psychological preparation in sports is occasionally underestimated or limited to achieving psychological readiness just before competition. Psychological methods are seldom integrated across the entire training process to enhance the effectiveness of athletes' training [30]. The study found that athletes in the hypoxia group had a statistically significant improvement in their complex reaction times after following the theta/beta1 protocol with a simulated altitude of 2500m above sea level. No comparable alterations were noted in the normoxia group. Nevertheless, this supports prior scientific research suggesting that athletes can develop targeted neural brain activity in hypoxic conditions, resulting in improved performance [31]. Furthermore, it enhances previous studies that demonstrate the beneficial effects of several biofeedback training techniques on visual perception and the decrease in athletes' reaction times [32], particularly in normobaric hypoxic environments.

The acquired results align with prior findings indicating that enhancing beta1 wave activity and suppressing theta waves in the motor cortex enhances visual attention-related activities. Preliminary research indicated that the synchronization of beta brainwaves immediately before the presentation of a stimulus was the most reliable indicator of how quickly a task would be performed [33]. EEG biofeedback training was conducted on two research groups. The first group was trained to strengthen theta waves, while the second group was trained to suppress this frequency. The results showed that reducing theta activity led to improved performance in a test task. This also demonstrated the feasibility of selectively altering the frequency of brain waves [34,35]. Nevertheless, a constraint of this study was the limited quantity of training sessions and the absence of monitoring concurrent alterations in neuronal activity that may have accompanied the decrease in theta waves. Consequently, it was not feasible to ascertain whether this reduction was linked to an augmentation in alpha, beta, or a combination of both frequencies.

Egner and Gruzelier [36] investigated the efficacy of utilizing SMR and beta1 procedures to enhance perceptual capacities. The participants were categorized into three groups: the first group received reinforcement of SMR waves, the second group received reinforcement of beta1 waves, and the third group, which served as the control group, did not undergo any intervention. The examination of the results revealed heightened perceptual sensitivity in the SMR group and a notable decrease in reaction times in the beta1 group, while no statistically significant disparities were observed in the control group [36]. In their study, Ghaziri et al. [37] found that EEG biofeedback training had a positive effect on focus. They also discovered that beta1 band stimulation led to improved visual and auditory attention efficiency. Furthermore, they exhibited alterations in the composition of white and gray matter due to the neurofeedback intervention, thus presenting proof of its efficacy [37].

The outcomes of this study indicate that reinforcing the beta1 band at the C3 point has a good effect on enhancing the visual reaction speed of judo competitors. Additionally, they validate earlier findings that indicate that the activation of the beta band in the left hemisphere with open eyes may serve as an indicator of effectiveness in training [38]. EEG biofeedback training, utilizing the beta1 protocol, was administered by Gruzelier et al. [39] at the C3 location. This intervention yielded favorable outcomes, including a decrease in the frequency of errors and enhanced consistency in reaction times [39]. In this study, it was observed that judo athletes experienced positive changes in their reaction times after undergoing EEG biofeedback training at the C3 point. This confirms the positive influence of therapies that focus on strengthening beta1 brainwaves in this specific domain concerning enhancing athletes' visual attention.

The study employed EEG-biofeedback, a technique centered around the self-regulation of brain wave frequencies, specifically Beta and Theta waves. The conducted training sessions and their effect on enhancing both simple and complex reaction times were analyzed. This study specifically examines a cohort of judo athletes with different degrees of expertise, providing valuable context for understanding the correlation between the skill level and the efficacy of training. The research corresponds with fundamental principles in neurofeedback, which are crucial for evaluating the outcomes of studies on its efficacy in sports [9].

In this study, the theta/beta1 training protocol was executed under normobaric hypoxia with a simulated altitude of 2500m above sea level. The duration of the training was 20 minutes. It has been demonstrated that rest in hypoxia for 60 minutes is the shortest designated period causing cognitive function and mood state decline in men [40]. Nonetheless, Chroboczek et al. conducted a study that revealed that cognitive decline occurred after just 30 minutes of acute exposure to normobaric hypoxia at a simulated altitude of 3500 m (FIO2 = 13%) [41]. Another study by Chroboczek et al. [42] aimed to investigate whether progressive stages of normobaric hypoxia (FIO2 = 13%, FIO2 = 12%, and FIO2 = 11%) have varying impacts on cognitive performance after exposure. The study involved a cohort of fifteen physically active males, and cognitive function was assessed using the Stroop test (ST). Exposure to normobaric hypoxia led to significant cognitive impairment, particularly under FIO2 = 13%. No changes were observed in the Stroop test following exposure to FIO2 levels of 12% and 11% [42] indicating that the response to exposure may be influenced by the duration of exposure and the amount of hypoxia [43].

However, Pavlicek et al. [44] and Taylor et al. [45] found no significant alterations in cognitive function, specifically word fluency and word association, after 30–45 minutes of exposure to simulated altitudes ranging from 2440 m to 4500 m. Buck et al. [46] and Otis et al. [47] also reached similar conclusions in their respective studies. The study indicated that mild hypoxia, simulated at altitudes of 2400 and 3000 meters, does not affect cerebral blood flow, with a cut-off value of FIO2 set at 15%. This implies a potential threshold for such alterations, according to Buck et al. [46] and Otis et al. [47].

The response to normobaric hypoxia exposure seems to be heavily reliant on numerous factors such as participants' age, fitness level, health status, type of cognitive task, the mode and protocol of hypoxia (normobaric/hypobaric, intermittent/continuous) and the time performed post-test, among other confounding factors analyzed.

These results have been observed in previous studies [43,48,49,50], and are in line with the outcomes illustrated in research by Pramsohler et al. [51]. The authors demonstrated a notable rise in cognitive reaction time at 5500m altitude when compared to a simulated altitude of 3500m. Nevertheless, in their view, simulated altitudes did not appear to impact reaction times for uncomplicated tasks. However, this study has a limitation in that the tests were only conducted immediately following the task. Additionally, the subjects spent one night at a lower altitude and the next night at an altitude of 5500m, which could have overlapped stimuli in the subjects [51].

Hypoxia may have beneficial effects on neurogenesis and cerebral vascularization, as well as the acceleration of cerebral blood flow, which could all lead to improved cognitive performance. To achieve such positive outcomes, it is crucial to determine the appropriate exposure time or to establish adequate oxygen desaturation levels. Furthermore, it is important to consult relevant references for technical term abbreviations, such as Rybnikova [52] and Zhu [53]. It should be noted that individual responses to hypoxia exposure are highly variable, as previously described [53]. Proper adjustment of exposure parameters is therefore paramount. Several studies have reported that training in a normobaric hypoxia environment can improve an athlete's functional state and performance during competition [54–59].

5. Conclusions

In summary, the study investigated the impact of EEG-biofeedback training on Beta and Theta waves in normoxia and normobaric hypoxia conditions, and its effect on simple and complex reaction times in judo athletes during the Vienna Test. The results are promising, suggesting that neurofeedback training in normobaric hypoxia conditions may significantly improve reaction skills, particularly complex reactions, in a sports context. However, to gain a more comprehensive understanding and confirmation of these effects, further well-controlled studies are necessary. Long-term observations and the consideration of additional factors may provide a more complete picture of the impact of psychological training on athletic achievements.

6. Practical implications

In the context of sports practice, this study's results have potential implications for coaches, sports psychologists, and judo athletes. The study suggests that EEG-biofeedback training, focused on regulating Beta and Theta waves, could be an effective tool in improving reaction times. This type of training may be particularly beneficial for sports where a quick reaction to stimuli is crucial, such as judo. Coaches could integrate neurofeedback training into their training programs to enhance the psychological effectiveness of their athletes. However, it is essential to tailor the training to the specific needs of each athlete due to individual differences among them.

7. Study limitations

Regarding the limitations of the conducted research, it seems that one limitation could be the time of EEG-BF training. Judo competition includes a time limit of 4 minutes which corresponds to the duration of a training series in our study. However, the 4 minutes refer to active time and do not take into account breaks or referee interaction. Therefore, a more specific protocol may be necessary for attention training to further improve the similarity of competition in judo.

In addition, reaction time was measured immediately after training. A normobaric hypoxic environment may negatively interact with cognitive performance, which could potentially affect reaction time results. It is unclear whether EEG-BF training under normobaric hypoxia enhances adaptations achieved under normoxia. It is possible that the effects could be more pronounced under normoxic conditions, once the potential decline in cognitive abilities induced by hypoxia has subsided.

8. Directions for future research

Based on the results of this study, certain directions for future research are suggested. It would be crucial to expand the research sample, consider different levels of sports proficiency, and analyze the long-term effects of EEG-biofeedback training. Additionally, researchers could contemplate incorporating other forms of psychological training to compare their effectiveness with neurofeedback training. Comparing different methods could yield valuable insights into optimal strategies for enhancing athletes' reaction skills.

Finally, further studies should also take into account practical aspects of implementing neurofeedback training into training programs, such as equipment availability and training time requirements. Ultimately, a holistic approach to the psychological preparation of athletes requires consideration of various effective strategies, each tailored to the athletes' individual needs.

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