SPORT TK-EuroAmerican Journal of Sport Sciences

https://revistas.um.es/sportk Online ISSN: 2340-8812

Received: **27/04/2025.** Accepted: **28/08/2025.** Published: **19/12/2025**

The effect of Neurofeedback SMR training on psycho-physiological and behavioral phenomena in professional handball players: An exploratory study

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ABSTRACT

This study aimed on examining the effects of Sensory Motor Rhythm training (SMR-T) on various psychophysiological and behavioral phenomena in professional handball players. The study involved ten handball players, with no prior experience in neurofeedback training, four undergoing the SMR-T protocol and six serving as the control group. Using a small-N, multiple-measures design, changes in reaction time, focused attention, general and pre-competition anxiety were monitored, while interviews assessed the subjective experiences and perceptions of the protocol's effects in the experimental group. Quantitative analysis based on descriptive parameters revealed a mild tendency towards improvement in pre-competition anxiety in the control group, while much stronger tendencies for improvement were observed in the experimental group across nearly all tested parameters, specifically regarding reaction time, focused attention, general anxiety, and pre-competition anxiety. Inferential statistics, likely due to the small sample size, did not confirm statistically significant differences between groups after the intervention, except for general and pre-competition anxiety. However, moderate to strong effect sizes suggest that this method may have significant potential for impacting the outcomes measured. Qualitative findings also point to psychological benefits of SMR-T, including perceived reduction in pre-competition anxiety, enhanced focused attention, improved sleep, and other positive behavioral effects. The results suggest that SMR-T could be a valuable tool, not only for performance enhancement, but also for improving overall well-being in professional athletes.

KEYWORDS

Reaction Time; Anxiety; Focused Attention; Qualitative Research; Elite Athletes

1. INTRODUCTION

In modern sports, the use of advanced technologies for training and performance enhancement is becoming increasingly prevalent. One technology that has attracted the attention of experts due to its positive effects on various aspects of human functioning, both outside of sports (Gruzelier, 2014; Kondo et al., 2019; Marzbani et al., 2016) and within the sporting domain (Levy & Baldwin, 2019; Rydzik et al., 2023), is biofeedback and its subfield, neurofeedback.

Biofeedback, or neurofeedback training (NFT), is a non-invasive method based on the paradigm of instrumental conditioning. Using modern technology, an individual receives real-time feedback on their physiological parameters, enabling them to regulate these parameters and thus create conditions for better psycho-physical functioning. Specifically, in the case of NFT, the person receives insights into their brain activity – typically via electroencephalography (EEG) – through various signaling modalities (see Gong et al., 2021 for other modalities). Regulating brainwaves potentially results in improved cognitive and behavioral functions relevant to various domains, including sports performance. Brainwaves essentially represent oscillatory electrical activity produced by neural communication. Based on oscillation speed, measured in Hertz (Hz), there is general agreement on different types or ranges of brainwaves, which correspond to various states of consciousness and mental activity. The classic general ranges of brainwaves are delta (0.5-4 Hz; predominant during sleep and recovery processes), theta (4-8 Hz; linked to deep thinking, light sleep, relaxation, creativity, and memory formation), alpha (8-12 Hz; dominant in awake relaxed states and meditation), beta (12-30 Hz; intensified during focused work and information processing), and gamma (30-100 Hz; increased during high-level cognitive functioning). In addition to these general ranges, there are "derived" brainwave ranges, such as the sensorimotor rhythm (SMR) or low beta (12-15 Hz; linked to physical relaxation and preparedness) and high beta (20-32 Hz; intensified during peak cognitive performance, but also in states of worry, anxiety, rumination, and obsessive-compulsive behavior). For more information on brainwaves, see the work of John Demos (2005). Analyzing existing modalities of NFT in sports (SP-NFT), Gong and colleagues (2021) propose a classification of SP-NFT into four general schemes based on user experience: attention-focusing training scheme (the athlete trains their general ability to focus and sustain attention), simulated training scheme (the athlete attempts to simulate neural activity that occurs during successful performances), relaxation training scheme (the athlete relaxes their mind to regulate mood and reduce stress), and monitoring-guided training scheme (the athlete achieves a state of personal optimal arousal for successful performance). Given the prevalence of these schemes in current research, we decided to implement the most commonly used approach for this study: the attention-focusing training scheme, specifically the experimental paradigm commonly referred to as sensorimotor rhythm training (SMR-T). The SMR-T protocol primarily involves increasing the power of the SMR rhythm but often also involves a parallel reduction in theta rhythm power (Demos, 2005; Gong et al., 2021). This approach aims to inhibit drowsiness and absent-mindedness while enhancing presence and focus, resulting in a state known as relaxed focus.

The positive effects of SMR-T on various mental issues such as attention deficit hyperactivity disorder, anxiety, depression, epilepsy, insomnia, mood, and drug addiction (see Marzbani et al., 2016) have attracted the attention of researchers in the field of sports, leading to an interest in the effects of this training on different aspects of athletes' functioning (de Brito et al., 2022; Gong et al., 2020, 2021). Analysis of the relatively limited number of studies of this type indicates that the primary interest is in examining the utility of SMR-T for sports performance. The complexity and dynamic nature of sports have primarily directed researchers towards closed-skill sports. Results suggest that SMR-T can significantly improve accuracy in archery (Paul et al., 2011), and golf (Cheng et al., 2015). An exception to confirming the effects of SMR-T in open-skill sports is the work of Salimnejad et al. (2019) with rugby players, where passing accuracy was used as a performance parameter.

Given these limitations, it is justifiable to focus on the potential effects of SMR-T on psycho-physiological modifications indirectly related to sports performance. Reaction time, or the ability to timely perceive a stimulus and exhibit rapid, adequate responses, is undoubtedly an important prerequisite for good sports performance. A few researchers have focused on examining this phenomenon and confirmed that SMR-T can be beneficial for its improvement (Mikicin et al., 2015; Parsaee et al., 2018; Prończuk et al., 2023). Apart from reaction time, which is a cognitive-motor ability, a connection between SMR-T and exclusively cognitive parameters such as general attention has also been established (Mikicin et al., 2018). In addition to these domains, a few studies have investigated the potential effects of SMR-T on athletes' emotional states. Anxiety, generally understood as a negative emotional state characterized by worrying thoughts about future outcomes accompanied by negative physiological changes, is one of the primary issues athletes face and thus a key target for experts developing strategies to reduce it. Considering this, it is encouraging that Faridnia et al. (2012) reported that SMR-T led to a reduction in competitive anxiety among swimmers. On the other hand, Paul et al. (2011) examined the effects of SMR-T on other emotional states and found positive changes, including a more optimal pre-competition state of pleasure and arousal, as well as post-competition arousal, in archers who underwent twelve sessions of SMR-T.

The promising results of previous research on the application of SMR-T in sports motivate further exploration of this approach, which inherently raises a number of scientific-methodological questions. Regarding the SMR-T protocol, questions arise about the optimal number of frequency ranges to manipulate (only the SMR rhythm or a combination with theta and high beta rhythms), the most effective feedback signals (visual, auditory, tactile, or a combination), and the protocol's time frame (duration of individual training sessions, number of sessions per week, and the overall duration of the program). As for participant characteristics, various specific factors must be taken into account, such as gender, age, level of sports skills, and others. It is also important to monitor the effects of these training sessions across multiple dimensions of human functioning (sports performance, cognitive-motor capacities, motivation, emotional-social aspects, general and specific satisfaction, etc.).

These potentials, but also the limitations of current insights, are the main motivation for this study. Its goal is to examine the effects of the appropriate SMR-T protocol on various psycho-physiological aspects of elite handball players, as well as to gain insights into their subjective experiences during the training and their self-assessment of the effects on various behavioral aspects. The hypothesis is that handball players who undergo the SMR-T protocol will improve their focused attention and show stronger tendencies to improve reaction speed, along with stronger tendencies to reduce general and pre-competition anxiety compared to their peers who did not undergo neurofeedback training. It is also expected that participants in the SMR-T protocol will report positive subjective experiences of the training and positive effects on their attention, social functioning, stress management, decision-making, mood, sleep, and other behavioral aspects, both in sports and outside of it. We hope that the results of this research will provide further insights into the effectiveness of the protocol and the potential benefits of SMR-T in sports, and strengthen its further application in improving sports performance and the psychological well-being of athletes.

2. METHODS

2.1. Participants

To conduct the experiment, 10 male professional handball players from the first team of the Handball Club Borac (aged 18 to 26 years) were engaged. At that time, the team was the reigning senior champion of Bosnia and Herzegovina and participated in the EHF European Cup competition. The participants were randomly assigned to either the experimental group (four players) or the control group (six players). Three players completed the entire experimental program, while the fourth player sustained an injury during a match in the second week of the experiment. Due to the limitation of the sample, we decided to retain the injured athlete in the SMR-T protocol for the transitional and final testing, but he was excluded from the pre-competition anxiety assessment due to his inability to compete. All athletes had no prior experience with neurofeedback training. All athletes were of legal age and provided written consent for voluntary participation in the study.

2.2. Measurements

The experiment was conducted from March to May 2023. Figure 1 shows the experimental design and research flow. Initial testing of the experimental and control groups was performed three days before the start of the SMR-T protocol. This testing involved measuring reaction time and general anxiety levels, followed by EEG signal recording at rest, which was conducted only with the control group. The SMR-T protocol was then administered to the experimental group twice a week (on Tuesdays and Thursdays) for 25 minutes over a period of 5 weeks (a total of 10 sessions). The control group did not have additional tasks. In addition to the initial testing, transitional testing (after five SMR-T sessions) and final testing (three days after the last SMR-T session) were conducted. Besides the tests used in the initial testing, an interview with the experimental group was conducted during the transitional and final testing phases to gather information about their experiences during SMR-T and its impact on their cognitive-behavioral functioning in various situations, both in sports and outside of it.

During the SMR-T protocol period, the team played 9 league matches (held on Wednesdays and/or Saturdays), and both the experimental and control groups completed a questionnaire 30 minutes before each match to assess their pre-match anxiety levels. Athletes who knew they would not participate in the game (e.g., due to injury) did not complete the questionnaire for that match.

2.2.1. Reaction time measurement

Reaction time was tested using the BlazePod™ reactive light system (Play Coyotta Ltd., Tel Aviv, Israel). The BlazePod system is based on a wireless sensor system in the form of lights that generate a signal in the form of reaction time from the time the light turns on and off. Results are displayed on a smartphone via the BlazePod app, which receives the signal through Bluetooth technology. This sensory system has a high level of reliability and is recommended for use in training practice and sports diagnostics (de-Oliveira et al., 2021; Hoffman, 2020). In this study, a total of six sensors were used, three in two rows, and were placed on a specially designed board in front of the participants. The height of the sensors was set individually based on the height of the participant, at shoulder level. The distance from the sensors was determined according to the length of the arms, which needed to be in a slight elbow flexion at an angle of 140-160º. The sensors, or reactive lights, were activated automatically in a randomized mode from 0.5 to 10 seconds, and were deactivated by the participant's palm strike on the sensor. Reaction time measurement was conducted in 3 blocks of 3 minutes each, with 2-minute breaks between blocks. The final reaction time score for the initial, transitional, and final measurements was obtained by calculating the average reaction time for the three blocks of testing.

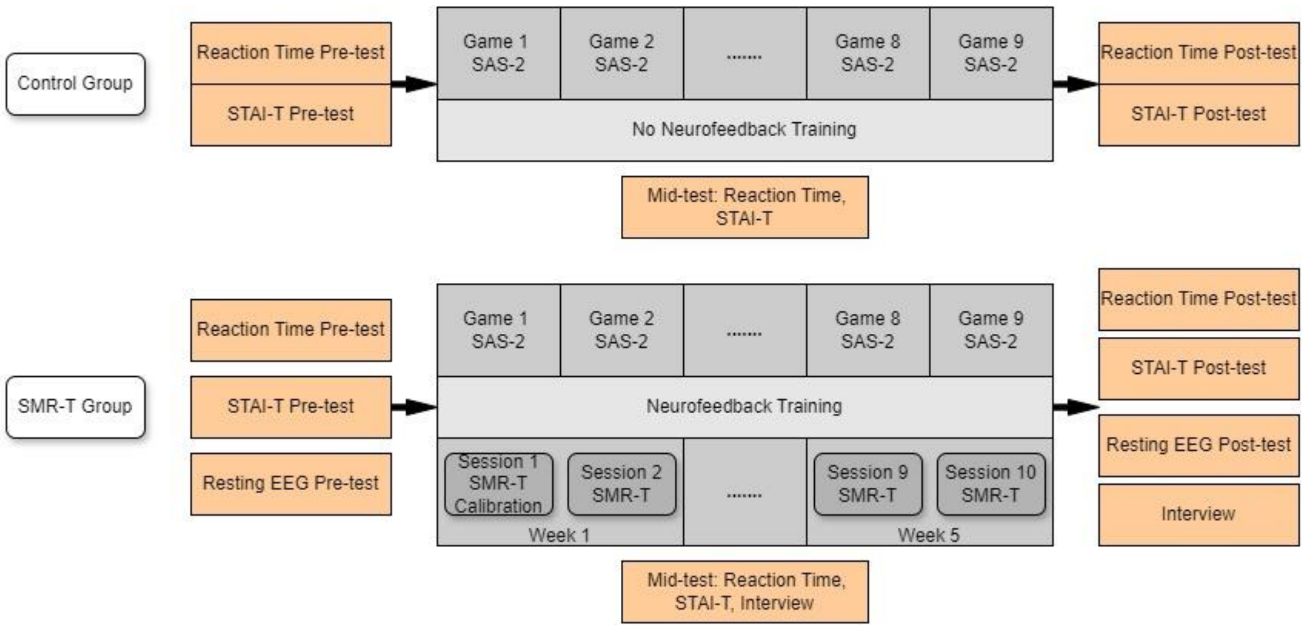

Figure 1. Flowchart of the Research Design and Process

2.2.2. Measurement of electrical brain activity

EEG signal recording at rest during the initial, transitional, and final phases was conducted for ten minutes. The participant was seated with their eyes open and instructed to remain physically relaxed and present while looking at a blank screen. The EEG signals were collected using the Mindmedia NeXus-10 MKII system (Mind Media B. V., Herten, Netherlands) with an accompanying ExG sensor at a sampling rate of 256 Hz and the BioTrace+ NX10 software. A single electrode was mounted on the midline central region of the head - Cz point (according to the 10-20 EEG placement system), with the reference electrode placed on the right mastoid and the ground on the left mastoid (see Figure 2). Impedance was monitored and did not exceed 5 kΩ. Using the "automatic artifact rejection" feature offered by the software, segments of the signal caused by muscle activity exceeding 5 µV (microvolts) were removed. Additionally, the software's filtering option provided average amplitude values expressed in µV for 5 frequency bands: theta (4-8 Hz), alpha (8-12 Hz), SMR (12-15 Hz), beta (13-21

Hz), and high beta (21-25 Hz). Based on these data, the theta/SMR ratio was calculated for the study, serving as a basis for examining the lasting effects of SMR-T on the electrical activity of these frequency bands obtained from baseline measurements.

2.2.3. SMR-T protocol

After the experimental group underwent a theoretical introduction to Neurofeedback Training (NFT), with a specific focus on SMR-T, they began individual training sessions. The electrode placement for SMR-T was the same as during baseline measurements, meaning that the feedback signal was based on activity recorded at the Cz point and was presented solely through a visual modality. The participant's task was to control the animation on the screen by continuously guiding a ball upwards (see Figure 3). The ball's upward movement occurred only when two conditions were simultaneously met. The first condition required maintaining theta amplitude below an individually set threshold, while the second required increasing SMR amplitude above a specified threshold. An additional control prerequisite was that the participant remains still during the training to avoid interference from electrical signals due to muscle activity. To achieve this, the participant received feedback on their muscle electrical activity via an electromyography (EMG) bar on the screen, and if the values on the bar exceeded 5 µV, the ball's movement was automatically halted. When the conditions were met, the BioTrace+ application automatically calculated the number of points scored based on an internal algorithm, which was displayed to the participant throughout the training session. For the first training session, the voltage threshold for the theta band was set 40% higher than the average amplitude value obtained during baseline testing (e.g., if the average theta amplitude of the participant was 10 µV, the threshold was set at 14 µV), while the threshold for SMR amplitude was set 30% below the average baseline value (e.g., for an average amplitude of 5 µV, the threshold was set at 3.5 µV). For all subsequent training sessions (from the second to the tenth), threshold calibration was performed. Specifically, the average amplitude values of the given frequency bands obtained during the first training session were used to determine the theta and SMR thresholds for these sessions, applying the same percentage principle. This adjustment was based on the logical premise that the baseline value for setting the training threshold should be derived from signals obtained under the same conditions as the training itself. Each training session consisted of two blocks lasting 10 minutes each, with a 3-minute break in between. During the break, the participant was instructed to relax, rest, and prepare for the next block.

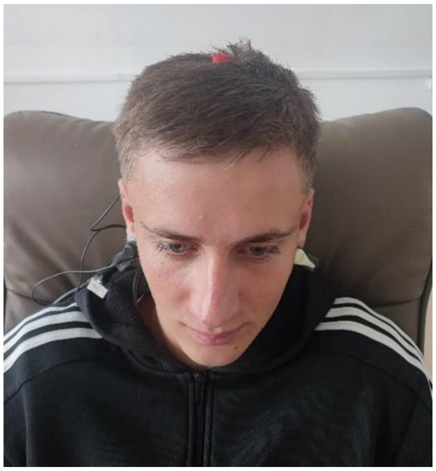

Figure 2. Electrode placement. The primary electrode was mounted at the midline central region – CZ point (red electrode), =hile the reference (black) and ground electrodes (white) were placed on the right and left mastoids, respectively.

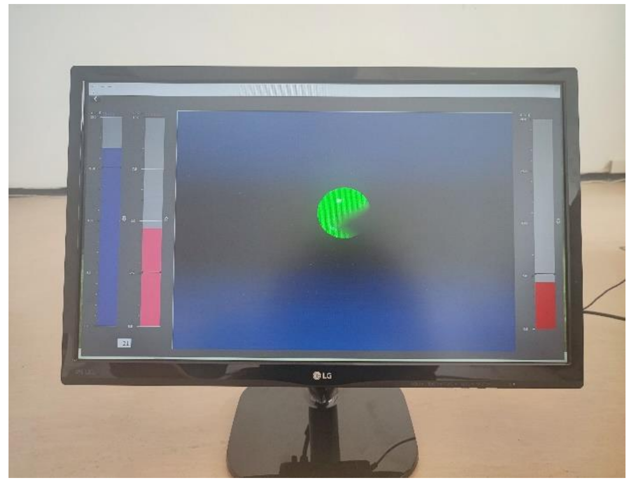

Figure 3. The animation used during SMR-T, labeled as "Balg" in the BioTrace+ application. If the specified requirements were met, the ball would move upward, and when it reached the top of the screen, it would "exit" and reappear at the bottom of the screen, prompting the participant to continue with the task.

2.2.4. Measurement of general and pre-competition anxiety

To assess general anxiety, the State-Trait Anxiety Inventory – STAI (Spielberger et al., 1983) was used, specifically the form that examines anxiety as a relatively stable personality trait, labeled as STAI-T. This form consists of 20 statements indicating different aspects of anxiety, and the participant uses a five-point Likert scale (e.g., from "Almost Never" to "Almost Always") to express how often they feel the given state (e.g., "I worry too much over something that really doesn't matter"). The final score was obtained by summing all the items, resulting in a range from 20 to 100 points, with higher values representing a higher level of general anxiety. The authors report internal consistency coefficients ranging from .86 to .95, indicating high reliability of the STAI-T scale.

To assess pre-competition anxiety, the Sport Anxiety Scale - SAS-2 (Smith et al., 2006) was used. This instrument consists of 15 items, and for each, the participant uses a five-point Likert scale (e.g., from "not at all" to "very much") to express how they felt before or during the competition. SAS-2 is a multidimensional instrument, and for this study, two dimensions (subscales) were used: cognitive and somatic anxiety. The cognitive anxiety subscale, through five items (e.g., "I worry that I will play badly"), measures pre-competition worry or thoughts about performing poorly and disappointing others. The somatic anxiety subscale, also with five items (e.g., "my body feels tense"), examines the presence of negative bodily sensations before the competition. For the purposes of this study, the scores of the cognitive and somatic anxiety subscales were summed, as a very strong correlation was found between them ($r= .83$; $p< .001$). This created a total anxiety scale ranging from a minimum of 10 to a maximum of 50 points, with higher values indicating greater cognitive-somatic anxiety. The authors report high reliability coefficients for these scales, with a Cronbach's alpha of .89 for the cognitive anxiety scale and .84 for somatic anxiety.

2.2.5. Subjective experience and perception of training effects

In addition to quantitative approaches to assessing the effects of SMR-T, a qualitative approach was also applied in the study. A semi-structured interview was conducted with the experimental group on two occasions, after the 5th and 10th SMR-T sessions. The interview consisted of seven predefined open-ended questions, as well as subsequent "spontaneous" questions that arose during the interview to further clarify the given answers. The aim of this method was to gain insight into the athlete's subjective experience during the training and their self-assessment of the effects on various behavioral aspects (attention, communication, coping with stress, decision-making, as well as other factors such as motivation, mood, sleep, energy levels, etc.), both in sport and outside of it.

2.3. Data Analysis

This study is based on a small-N multiple-measures design, where both quantitative and qualitative approaches were used for data collection. The analysis of quantitative data included both descriptive and comparative statistical methods. Specifically, paired-samples t-tests and repeated-measures ANOVA were conducted to examine changes over time, as well as the interaction between time and group (experimental vs. control). Additional effect size analyses were also performed. Since the small data set does not allow for strong reliance on inferential statistical procedures, we focused on what is typically done in such studies—visual inspection of the data. This approach enables intuitive detection of changes in measurement patterns and emphasizes individual-level analysis (Graham et al., 2012). In addition, we supplemented the graphical representations with a simple quantitative measure of effect size commonly used in similar designs: the percentage of measures in later phases that fall below or above the median of the initial phase (Manolov et al., 2010). Regarding the qualitative data, transcription was first performed, allowing for thematic analysis. Thematic analysis is a method for analyzing qualitative data that involves identifying recurring ideas (called themes) within the dataset (Jason & Glenwick, 2016). Relevant statements from the interviews were coded into themes, interpreted, and presented.

3. RESULTS

3.1. Reaction Time

To examine whether there were changes in reaction time over time (initial and final measurements) for two different groups (experimental and control), a repeated-measures ANOVA was conducted. The obtained results [$F(1,8) = 1.460$, $p = .261$, $\eta^2 = .154$] indicate that no statistically significant interaction was found, meaning there were no significant differences in reaction time changes between the experimental and control groups. However, the effect size suggests a relatively strong interaction effect (Cohen, 2013), which implies that differences in reaction time between the experimental and control groups might still exist, but these differences were not confirmed as statistically significant, possibly due to factors such as small sample size. As a result, the focus shifted to the analysis of descriptive plots, i.e., the visual examination of data trends, presented in Figure 4. It is noticeable that the differences between the groups are evident only in the final phase, where the experimental group shows a tendency towards faster reactions. The average value of the final measurements in the experimental group (M = 418.5 ms) is faster by as much as 0.76 standard deviations compared to the overall average value of all participants in the first measurement (M = 443.4, SD = 24.9). In the control group, there is even a slight tendency towards slowing down, but this is primarily the result of visibly weaker results from two participants in the last three measurements. If we focus on the transitional tests, it is clear that the progress was not linear, which is confirmed by the negligibly higher number of results below the within-subject median when considering the six later measurements in the experimental group (54.2%) compared to the same number of measurements in the control group (47.2%). It can be assumed that the key change occurs only after six or more training sessions.

3.2. Electrical Brain Activity

The average amplitude values for 5 frequency bands were extracted from the data obtained by recording EEG signals at rest at the Cz point. A review of the data did not reveal any patterns in any of the frequencies that would suggest specific effects of SMR-T on baseline electrical brain activity. Therefore, only the relationship between two frequencies of primary importance to the study (theta/SMR ratio) is presented in the paper. SMR-T is based on the participant reducing theta and increasing SMR amplitude, which implies that if these trainings have lasting effects on brain electrical activity, the theta/SMR ratio values should be lower in later tests. The analysis of variance did not reveal statistically significant differences between the experimental and control groups over time in terms of the theta/SMR ratio, and the effect size also indicates a weak interaction effect [$F(1,8) = 0.089$, $p = .773$, $\eta^2 = .011$]. Regarding the descriptive plots, Figure 5 shows that participants in the experimental group did not exhibit the expected dynamics, meaning that handball players who underwent the SMR-T program did not display lasting changes in brain electrical activity. Although the control group did not undergo neurofeedback training, it is useful to observe the dynamics of their brain electrical activity over the three time points in Figure 5. Similar patterns are noted as in the experimental group. First, there is some variability in the three measurements for each individual, and second, there is no clear common dynamic when comparing the participants. This is also evident from the equal percentage of participants in both groups who had higher results in later measurements compared to the initial measurement. In the experimental group, this was 4/8 (50.0%), and in the control group, 6/12 (50.0%).

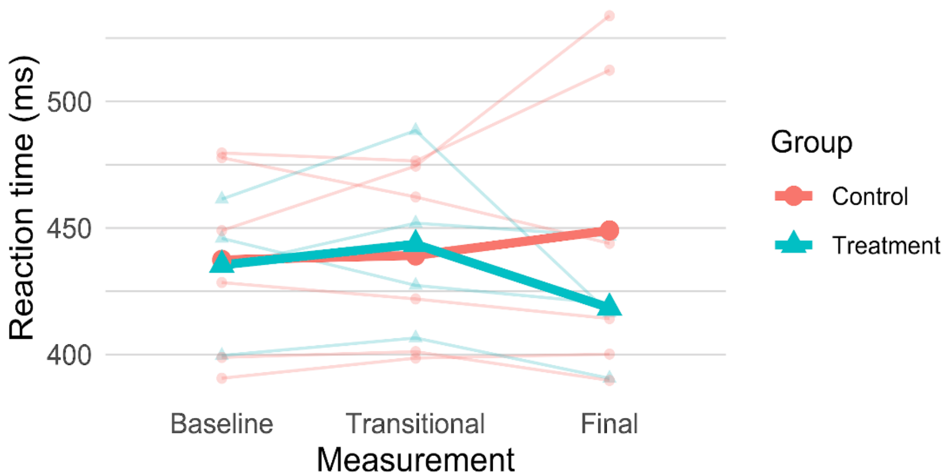

Figure 4. Average reaction time of participants expressed as the mean for three phases with three measurements each. Thin lines – values for individual participants, thick lines – average values for the group

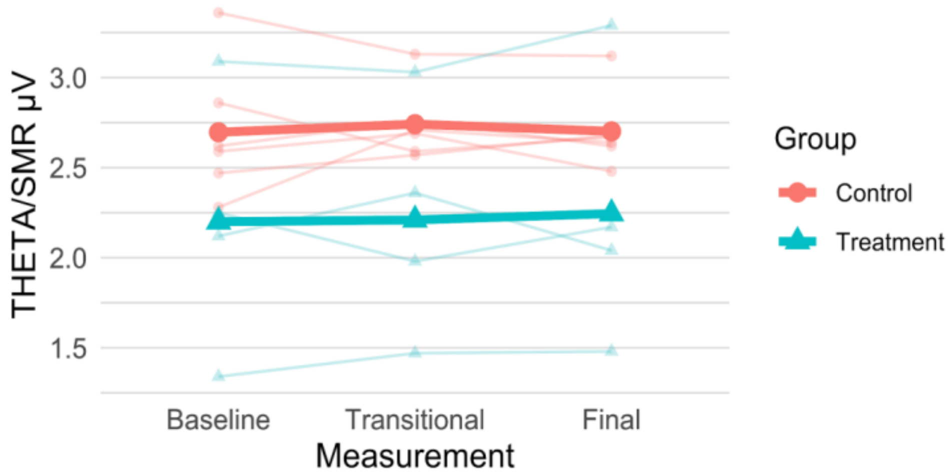

Figure 5. Theta/SMR amplitudes in the experimental and control groups. Thin lines – values for individual participants, thick lines – average values for the group

3.3. SMR-T Score Dynamics

The performance of SMR-T was measured using scores from the BioTrace+ algorithm (higher scores indicate better performance). A paired-samples t-test, conducted to compare focused attention scores between the baseline i.e., initial (average value of the first three measurements) and final measurements (average value of the last three measurements) within the experimental group, showed no statistically significant difference. However, the effect size was small to moderate [$t(3) = -0.631$, $p = .573$, $d = -0.316$], indicating the need for further investigation of data trends through descriptive plots. Figure 6 shows scores achieved by 4 handball players in the experimental group during the 3 phases (9 neurofeedback sessions analyzed, while the first calibration session was excluded). The scores reveal significant variability between participants. Two participants exhibit a clear upward trend, one shows better results in the final phase compared to the initial phase with a drop during the transitional phase, while one - who had the highest score initially - shows a constant decline in performance and ends with the second-best score. Overall, in 54.2% of measurements, participants achieved better results compared to their median in the first three sessions.

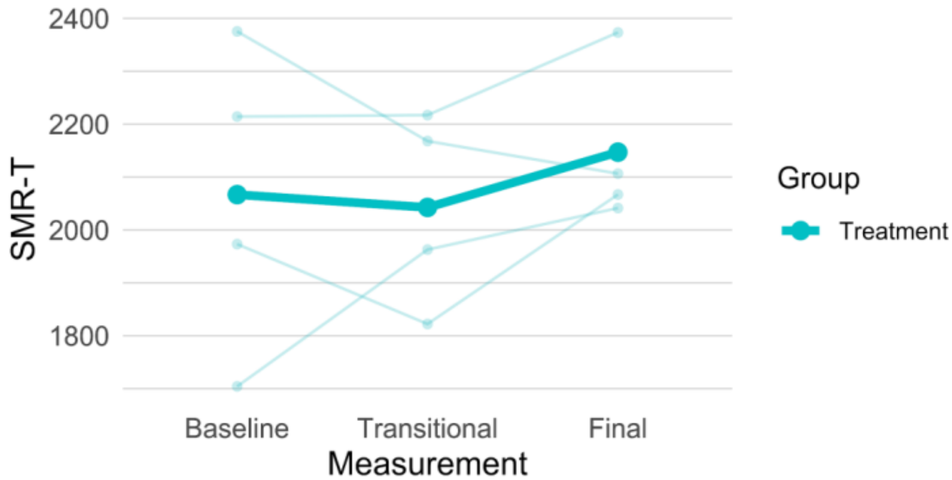

Figure 6. SMR-T scores of the experimental group participants expressed as averages for three phases with three measurements each. Thin lines represent individual participants, while the thick line indicates the average group values

3.4. Evaluation of General and Pre-Competition Anxiety

Analysis of variance revealed significant differences over time (initial - average value of the first three measurements, final - average value of the last three measurements) between the experimental and control groups in terms of general anxiety, with the obtained partial eta squared values confirming large effect sizes [$F(1,8) = 7.92$, $p = .023$, $\eta^2 = .498$]. It can be concluded that the intervention had a differential effect, resulting in a more pronounced reduction in general anxiety in the experimental group. Figure 7 shows the anxiety values as general tendencies for participants in both the experimental and control groups, obtained from three measurements at three time points. A trend of decreasing anxiety is evident in the experimental group, whereas the final value in the control group remained similar to the initial value. Moreover, all four handball players undergoing the experimental process had lower scores in the final measurement compared to the first, with a total of 7 out of 8 later values being lower than the self-assessment before treatment (87.5%). In the control group, this was the case in only 4 out of 12 measurements (33.3%), with three of six handball players showing higher values in the final measurement compared to the initial one.

In addition to general anxiety, pre-competition cognitive-somatic anxiety was monitored. Just before each of the 9 matches, players self-assessed their anxiety. Examining the differences between the initial measurement (average of the first three measurements) and the final measurement (average of the last three measurements) for both groups, it was found that, over time, the experimental group showed a significant reduction in pre-competition anxiety compared to the control group, and the partial eta squared value indicates a strong effect of the interaction [$F(1, 6) = 6.657$, $p = .042$, $\eta^2 =$

.526]. Figure 8 tracks the dynamics of trends of average values across the three phases of the study. It should be noted that one participant from each group missed 4 or more matches and was excluded from further analysis. Figure 8 indicates that, over time, there is a decrease in pre-competition cognitive-somatic anxiety in both groups, but this trend is more pronounced for participants in the experimental group. This is supported by the difference between the median during the first three measurements and the subsequent six measurements: in the experimental group, 94.4% of scores were lower compared to the median of the initial phase, while in the control group, this percentage was significantly lower (72.8%).

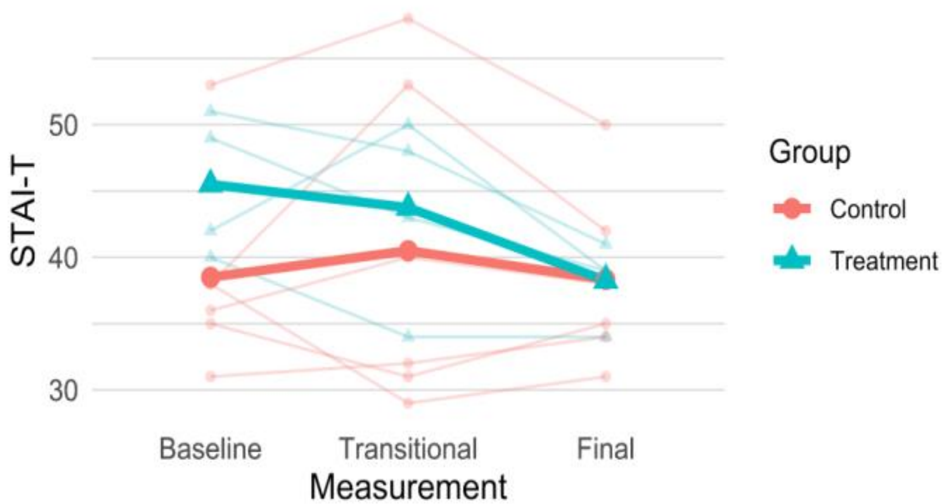

Figure 7. General anxiety at initial, transitional, and final measurements

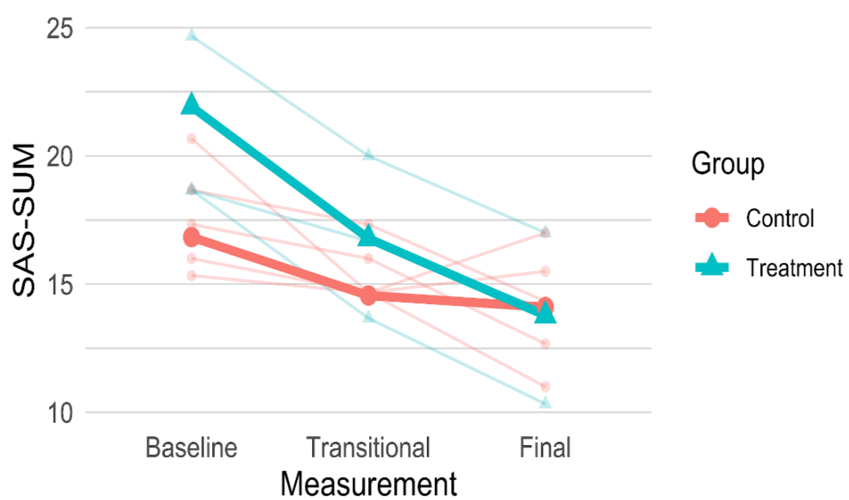

Figure 8. Pre-competition cognitive-somatic anxiety during the initial, transitional, and final phases

3.5. Subjective Experience and Perception of Training Effects

Interviews with the experimental group were conducted on two occasions: after 5 SMR-T sessions and after completing all 10 training sessions. The aim was to investigate the impact of SMR-T on various aspects of human functioning, such as attention, decision-making, handling pressure, collaboration with others, as well as motivation, mood, sleep, and more. After five SMR-T sessions, participants reported positive changes in emotional relaxation, reduced anxiety, and increased emotional stability. Greater focus on the field and the ability to maintain performance were also frequently mentioned. One participant said: "*I noticed that when my thoughts start to wander, I just focus, center myself, mainly on my breathing, and then I focus and concentrate much faster*." Most participants reported reduced impact from external distractions, such as noise from the stands, described as "*when the audience says something, I hear that something is being said, but I don't hear the exact words*." Participants also noted being more satisfied with their performance and having increased confidence on the field, while two mentioned better stress management and pressure handling, reflected in easier decision-making, reduced reactions to criticism, and greater ability to think constructively in complex situations. Three participants noticed improved concentration off the field, for example: "*…when I sit down to study, my concentration was a bit weaker before, but now I can maintain concentration much longer*." Improved sleep quality was also reported, as one participant described: "*…I think I have better sleep and sleep more than before. It lasts longer (...) and I fall asleep much easier*." Three participants mentioned that the neurofeedback training was initially exhausting. They noted it took extra energy, required a lot of concentration, and was tiring for the eyes, but they adjusted.

After completing all the training sessions, the interviews were repeated, with athletes continuing to report reduced distractions from external factors and increased focus on the game. "*…I don't look around, at the stands, the score," "I don't pay attention to what the opposing players say*." The increased ability to concentrate also extended to other aspects of life, including academic and everyday tasks: "*…when I work on the laptop, I focus more easily, I play some music on the laptop, which further relaxes me. I work on what I need until I finish. Nothing distracts me*." Unlike the first interview, in this one, all three participants reported improvements in stress management, indicating better ability to stay calm in challenging situations, which further reflected in motivation and confidence. One participant said: "*…I am somehow much more relaxed in the last few games. I feel relaxed, I want to play and everything, ... I'm calm, so to speak*." Additionally, unlike the first interview, now all three participants observe quicker and easier decision-making, both on and off the field. One participant said: "*…I know I was quite impatient and only wanted to get rid of the ball. Now I somehow enjoy every moment of the game and have patience when the ball is with me*." Two participants noted progress in interpersonal skills, improved communication and cooperation with teammates, and in personal relationships: "*I used to be quite withdrawn, didn't want to talk and kept everything to myself...I kept it to myself and wouldn't say how it is*," while one participant did not notice any positive effects in this area. Improved sleep quality was also confirmed again: "*…I noticed I fall asleep more easily in the evening than before and my sleep is somehow deeper*," though one participant did not have sleep issues and did not notice any positive or negative changes. One participant who was injured at the beginning of the experimental program could not observe positive or negative effects on the sports field, as he did not participate in competitions, but provided insights into the impact of neurofeedback training on everyday life. He noted improvements in attention during reading: "*…I read a book. I can keep focus much better and my thoughts don't wander, I don't start reading (...) while I'm somewhere else*," as well as improvements in conversations with others: "*Before, I used to look away while talking to someone and didn't hear what they were saying, but now it's much better*," though he did not notice significant differences in stress management.

4. DISCUSSION

The limited number of scientific studies on the application of SMR-T in sports, particularly in the context of high-level competition, motivated us to examine the effects of the SMR-T protocol on various psychophysiological aspects of elite handball players and to analyze their subjective experiences and self-assessments of its impact on behavior. Although the study is based on a small-N multiple-measures design, the obtained results are encouraging. For better clarity, the discussion of these results is organized into separate segments corresponding to the research questions.

4.1. Effects of SMR-T on Reaction Time

Inferential statistics did not confirm statistically significant differences in reaction time changes over time between the experimental and control groups; however, the effect size suggested the possibility of differences. Given the results and the small sample size, we focused on a more detailed analysis of the data trends using descriptive methods. The analysis of the descriptive plot revealed that three out of four participants in the experimental group showed improved final reaction times compared to their initial reaction times, while in the control group, three out of six participants showed similar improvements. Due to the small sample size and the applied statistical method, we cannot make general conclusions about the positive effects of SMR-T on reaction time enhancement, however, the obtained results imply that such tendencies exist. This aligns with several previous studies confirming these relationships (Mikicin et al., 2015; Prończuk et al., 2023), although it should be noted that the mentioned studies had sample sizes 2.5 to 3.5 times larger. It is true that our research focused on a sample of elite athletes, which presents significant challenges due to the complexities of conducting research within their demanding training schedules and competitive programs, unlike the aforementioned studies, which included students and athletes at the national level. In addition to the differences in sample size and type, there are also methodological differences. Mikicin and colleagues (2015) conducted 20 neurofeedback training sessions (each session consisting of 6 blocks of 5 minutes), and the experimental group participants also performed autogenic audio-visual relaxation at home for 45 minutes after each sports training. A higher number of NFT sessions compared to our study (15 in the first round and 15 after a four-week break) was also identified in Prończuk et al. (2023), though their training lasted 10 minutes. Both of these studies used visual-auditory feedback, while our study's feedback was based only on visual information. Considering this, we can hypothesize that applying a greater number of neurofeedback sessions with both visual and auditory feedback would lead to a more significant improvement in reaction time than the experimental protocol we implemented.

In addition to the number and duration of training sessions, the heterogeneity of existing experimental protocols is reflected in the use of different instruments for measuring reaction time and the sample of participants. The two mentioned studies involved national-level athletes, whereas our study involved professional international athletes. This raises questions about differences in the potential for improving reaction time among athletes who have reached a higher level of sports expertise compared to those at a lower level, as well as the number of neurofeedback sessions needed to achieve significant progress among athletes of varying levels of sports success.

4.2. Long-Term Effects of SMR-T on Electrical Brain Activity

The aforementioned studies (Mikicin et al., 2015; Prończuk et al., 2023) not only confirm significant long-term effects of neurofeedback training on reaction time but also observe substantial modifications in electrical brain activity within targeted frequency ranges during baseline EEG recordings (at rest without feedback). In this study, we focused on calculating the ratio of two targeted frequencies (theta/SMR) and tracking the trends of this relationship over three time points. Given the nature of the neurofeedback training protocol (reducing theta and increasing SMR amplitude), we expected that individuals in the experimental group would show a decrease in the value of this ratio over time, but this did not occur. The explanation for this likely lies in the number of SMR-T sessions conducted, as the two cited studies implemented a significantly greater number of training sessions than was done in this study. Authors of similar studies caution that neurofeedback is a long-term process (Blumenstein et al., 2012; Gani et al., 2008) and that there are cases where significant long-term changes in electrical brain activity were not observed even after 16 sessions (Logemann et al., 2010). Besides the number of training sessions, the density of training units also proves to be of great importance. Research conducted by Domingos et al. (2021) concluded that conducting three training sessions per week, rather than two, leads to more effective changes in targeted amplitudes, and that significant improvements in the performance of neurofeedback tasks (applications in the form of video games requiring successful goal achievement, e.g., “oddball”) were confirmed only with this denser NFT protocol.

4.3. Acute Effects of SMR-T on Electrical Brain Activity – Focused Attention

If significant changes in electrical brain activity require a considerable number of neurofeedback trainings, the question arises about acute effects, specifically the dynamics of targeted frequency bands during the actual training. The SMR-T scores generated by the software allowed us to track these dynamics. Scoring is based on meeting both conditions: the participant had to decrease theta and increase SMR amplitude, at which point the counter began awarding points. The longer the participant remained in this state during the 10-minute blocks, the more points they accumulated. Inferential statistics did not show significant differences between the initial and final states in the experimental group, but the moderate effect size suggests the presence of potential differences. A review of descriptive plots of SMR-T scores shows that three participants exhibited a trend of improving results, meaning they tended to remain in the desired state, identified as focused attention, for longer periods as the number of training sessions increased. The question arises as to why these trends were not observed in the fourth participant. One possible explanation is that this participant sustained an injury during a match that occurred between the third and fourth SMR-T sessions. Although he could not continue participating in other aspects of the experiment, we decided to keep him in the SMR-T program due to the small sample size. An examination of his SMR-T scores revealed that he showed progress up until the third training, after which a decline was noted. We can assume this was due to a loss of motivation, given the seriousness of the injury and his inability to return to training until the end of the season. The lack of progress in SMR-T scores may also be attributed to other factors. A significant number of neurofeedback studies indicate that there is a considerable proportion of non-responders (about 20-30%) who, for currently unexplained reasons, have not been able to regulate their brain activity (see Enriquez-Geppert et al., 2014). Modifying the SMR frequency band has proven particularly complex, with researchers reporting significant changes only after the 12th training session (Paul et al., 2011).

4.4. Effects of SMR-T on Athletes' Anxiety States

Emotions represent a highly significant, if not central, aspect of sports activities (Vallerand & Blanchard, 2000), and investigating the effects of neurofeedback training (NFT) on them should be one of the research priorities, which has not been the case so far. Stress, or anxiety, is a leading concept in research on emotional aspects of sport (Scanlan et al., 2005), and this study examined the effects of SMR-T on both chronic anxiety and specific pre-competition anxiety states. The results of inferential statistics indicate that the intervention had an effect, significantly reducing pre-competition anxiety in the experimental group compared to the control group. A review of the dynamics of trends in descriptive values, both individually for each participant and for the groups, revealed that all three handball players in the experimental group showed pronounced tendencies for a decrease in pre-competition anxiety over time. In the control group, three out of five participants exhibited a mild trend toward reduced anxiety, but they experienced more pronounced variations in anxiety levels from game to game. Nevertheless, it is essential to acknowledge that the initial group allocation was not balanced, as the experimental group exhibited higher baseline levels of pre-competition anxiety, which may have contributed to a more pronounced reduction following the treatment. The positive impact of NFT on pre-competition anxiety is supported by Faridnia et al. (2012), where a SMR-T protocol with 12 sessions was applied to 20 professional swimmers. It should be noted that in that study, the control variable was general pre-competition anxiety (how participants generally feel before competition), whereas in our study, we used a measure of specific pre-competition anxiety, i.e., anxiety measured before each individual game. Regarding the relationship between NFT and pre-competition emotional states, we identified only one other study addressing this issue, which confirmed that such training positively affects and increases pre-competition satisfaction (Paul et al., 2011). It should be noted that in these two identified studies, the sample size was 2-2.5 times larger than in our case.

Similar results were obtained when examining general anxiety. Over time there was a significant reduction in general anxiety in the experimental group compared to the control group, with large effect sizes indicating substantial differences. Visual inspection of the data trends obtained descriptively indicated that all four participants who completed the experimental protocol showed a trend of decreasing general anxiety in everyday life. In contrast, the control group showed no such trends, as only two out of six participants exhibited a decrease in anxiety over time. While these findings support the potential of SMR training in reducing anxiety, it is worth noting that the groups were not fully balanced at the start, which should be considered in future studies. In addition, the small sample size limits the strength of our claims, and we therefore do not have sufficient evidence to draw general conclusions. However, the presented data provide considerable optimism about the potential of NFT, specifically SMR-T, as a reliable method that can positively affect both chronic and specific anxiety states in athletes. Future research should not only attempt to confirm these conclusions, primarily by expanding and balancing the sample size, but also address questions regarding the most optimal protocols, which other emotional states may be positively influenced, and, perhaps most importantly, the psycho-physiological mechanisms underlying these interactions.

4.5. Subjective Perception of SMR-T Effects on Various Behavioral Aspects

Interviews conducted with the experimental group after five and after completing all ten neurofeedback training sessions provided valuable insights into the impact of SMR-T on various aspects of functioning. Participants consistently reported improvements in emotional relaxation, reduced anxiety, and increased emotional stability, which in turn enhanced their concentration, decision-making, stress management, and interpersonal interactions both on and off the field. The primary benefits noted included improved concentration and performance sustainability, reduced impact of external distractions such as crowd noise, and better stress management, leading to quicker decision-making and calmer responses to criticism. Additionally, significant improvements in sleep quality and duration were also reported, suggesting that SMR-T has a broad positive effect on overall well-being.

Participants also pointed out some challenges associated with neurofeedback training. Although the sample size was very small, and experiences varied among participants, some common conclusions can still be drawn. The training required a significant amount of energy and concentration, and participants often experienced discomfort due to eye strain, requiring time to adapt to the given conditions. These findings suggest the need for a gradual introduction of the protocol or adjustments to the intensity of the training to facilitate easier adaptation for participants. We believe that individual optimization of intensity can help prevent initial negative experiences and ensure athletes remain motivated to continue neurofeedback training.

The use of objective parameters to track psycho-physiological changes is undoubtedly valuable. However, to complete the picture, we believe it is crucial to also consider participants' subjective experiences, as this approach can provide an invaluable source of information. While subjective experiences do not fully meet the scientific rigor of quantitative measures, they are key to understanding the overall impact of the intervention on the individual. These subjective evaluations can serve as a basis for future research, where important personal insights from participants would form the basis for determining research variables to be subsequently examined using quantitative scientific methods. We believe that this combination of qualitative and quantitative methods can provide a more comprehensive understanding of the effects of neurofeedback training on individuals and recommend that future research consider this dual approach.

5. CONCLUSIONS

The investigation of the SMR-T protocol's effects on handball players has provided some intriguing insights into the potential of this approach in working with athletes, but it has also revealed certain limitations that future research should address. The limited number of participants is likely the primary reason why inferential statistics did not confirm a significant effect of SMR-T on reaction speed and focused attention. However, both descriptive statistics and the obtained effect sizes indicate positive trends that align with several previous studies, which is encouraging and suggests this possibility. This provides a strong argument for further research and hope that neurofeedback training could be a valuable tool for enhancing such crucial predispositions for good sports performance.

SMR-T has shown a positive impact on reducing pre-competition anxiety and general anxiety, indicating its potential as a tool for athletes' mental preparation. Additionally, participants' subjective experiences of improved emotional relaxation, concentration, stress management, as well as interpersonal interactions and sleep, suggest that this approach has the potential to achieve broader positive effects on both performance and overall well-being.

Although neither inferential nor descriptive parameters revealed certain tendencies towards permanent changes in participants' electrical brain activity after the SMR-T intervention, previous studies that employed a greater number of training sessions did record such changes. Differences in methodological approaches among existing studies, including the number and duration of training sessions and the type of feedback provided, highlight the need for protocol standardization. Existing results suggest that a higher number of training sessions and a combination of visual and auditory feedback might yield more significant results. The combination of qualitative and quantitative research methods could also enhance the understanding and validation of neurofeedback training effects.

While the results of this study are optimistic, further research is necessary to confirm these findings and establish optimal neurofeedback training protocols. One of the key directions for future research is addressing the sample size, as the small number of participants in this study represents a significant limitation. In addition to increasing the sample size, future studies should also ensure that groups are properly balanced based on their initial conditions. It is also important to consider that this research focused on elite athletes, a group that is difficult to access for studies involving complex experimental methods. Previous studies, which did not involve elite athletes, had sample sizes two to three times larger and reported more pronounced effects. Therefore, future research should aim to replicate this study with a larger, more balanced, and more diverse sample of athletes.

Besides that, it is also important to explore potential effects of SMR-T on other psychological aspects and to better understand the mechanisms behind these effects. We hope this study contributes to expanding the knowledge base and inspires future research to identify training protocols that provide reliable long-term benefits for athletes through a comprehensive methodological approach.

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AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

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