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Session Frequency Matters in Neurofeedback Training of Athletes

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Abstract
Neurofeedback training has been an increasingly used technique and is taking its first steps in sport. Being at an embryonic stage, it is difficult to find consensus regarding the applied methodology to achieve the best results. This study focused on understanding one of the major methodological issues—the training session frequency. The aim of the investigation was to understand if there are differences between performing two sessions or three sessions per week in enhancement of alpha activity and improvement of cognition; and in case there are differences, infer the best protocol. Forty-five athletes were randomly assigned to the three-session-training-per-week group, the two-session-training-per-week group and a control group. The results showed that neurofeedback training with three sessions per week was more effective in increase of alpha amplitude during neurofeedback training than two sessions per week. Furthermore, only the three-session-per-week group showed significant enhancement in N-back and oddball performance after training. The findings suggested more condensed training protocol lead to better outcomes, providing guidance on neurofeedback protocol design in order to optimize training efficacy.

Keywords Neurofeedback training · Athletes · Individual alpha band · Session frequency · EEG

Introduction

The demand for excellence in sport has increased and new methodologies and tools have emerged in order to contribute to the athletes' success. Neurofeedback training (NFT) uses electroencephalography (EEG) to regulate the electrical activity of the brain, providing a way to adjust and improve cognitive performance. This can also lead to sport performance enhancement, since NFT has been shown to positively affect concentration and attention (Hammond 2007), balance (Maszczyk et al. 2018), and precision (Gallicchio et al. 2017). Therefore, retraining brainwave activity in order to improve cognition is another method that can boost sport performance.

It has been found that EEG activities are associated with a particular mental state or cognitive function (Thompson and Thompson 2015). Particularly, higher levels of alpha synchronization are associated with well-practiced and overtrained tasks in sport (Mirifar et al. 2017) and related to inhibition of conflicting or irrelevant information, which contrasts with desynchronization that relates to excitatory processes (Klimesch et al. 2007). Enhancement of alpha activity by NFT has shown benefits on processing speed (Angelakis et al. 2007), better memory function (Guez et al. 2015; Nan et al. 2012), reaction time (Ziółkowski et al. 2012) and focus on a concrete task (Hsueh et al. 2016). These results are in line with the neural efficiency hypothesis (Babiloni et al. 2010) that is based on the specific activation of a brain area for a given task while disengaging the irrelevant brain area for the same task (Haier et al. 1992). It is a phenomenon that can easily be found in sport and even more in elite athletes (Milton et al. 2007). Thus, alpha NFT that aims to enhance alpha activity shows large potential

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in enhancing cognition and even sports performance in athletes.

However, there is no consensus regarding the training sessions frequency (sessions per week) in NFT. Previous NFT studies applied one-session-per-week (Gruzelier et al. 2014; Mikicin 2015, 2016; Mikicin et al. 2015; Ring et al. 2015), two-session-per-week (Perry et al. 2011; Raymond et al. 2005; Shaw et al. 2012), three-session-per-week (Faridnia et al. 2012; Paul et al. 2012; Rostami et al. 2012), or every-day-of-the-week (Cherapkina 2012; Golovin et al. 2015) protocols. Furthermore, authors using similar protocols did not compare the efficacy of the existent methodology, and even when trying to replicate an already existing protocol the results are often contradictory. These authors indicate that the same protocol (inhibiting high alpha and increasing theta) in the same modality led to opposite results (Gruzelier et al. 2014; Raymond et al. 2005). However, when we look more closely, we realize that both Raymond et al. (2005) and Gruzilier et al. (2014) did 10 training sessions lasting 20 min but with different weekly sessions. The former completed the study in 4 weeks (~2.5 sessions per week) (Raymond et al. 2005) while the latter took 12 weeks (~0.83 sessions per week) (Gruzelier et al. 2014).

Therefore, in order to clarify the NFT session frequency in athletes, this study investigated the differences of NFT effects between a three-session-per-week protocol and a two-session-per-week protocol, in a total of 12 NFT sessions. The NFT effects included changes of both alpha activity and cognitive performance. Considering the large inter-individual difference in alpha frequency (Klimesch 1999), this study utilized individual alpha band (IAB) rather than fixed alpha band. To the best of our knowledge, no study has directly examined two different session frequency protocols under the same conditions in sport. The present study was conducted as a preliminary step in constructing a guideline related to the better frequency of sessions to maximize the outcome of NFT in sports.

Materials and Methods

Participants

This was a randomized study. A total of 45 male student-athletes (computed by G*Power software (version 3.1.9.4) for a 0.05 significance level and a 0.95 power before experiment) aged between 18 and 34 years (mean (M) ± standard deviation (SD): 21.20 ± 2.62 for the two-session protocol vs 22.60 ± 1.12 for the three-session protocol, $p = 0.464$) participated in the experiment during the normal academic period. Participants had to be involved in federated sports or practiced regular physical activity (minimum of 30 min of at least moderate intensity 5 times a week) (World Health Organization 2010) for more than 5 years (Baker et al. 2005). The inclusion criteria were as follows: (1) all the participants had no history of psychiatric or neurological disorders; (2) no psychotropic medications or addiction drugs; (3) normal or corrected-to-normal vision; (4) minimum age of 18 years and maximum age of 35 years; and (5) practicing vigorous exercise at least five times a week (sport or gym) regardless of skill level. Participants were randomized into three groups: (a) three-session-per-week intervention group, (b) two-session-per-week intervention group, and (c) control group without sham. All student-athletes were instructed about the investigation before providing written informed consent to participate. This study was carried out in accordance with the recommendations of local ethics guidelines and approved by the Ethics Committee of the Faculty of Human Kinetics, University of Lisbon. All participants gave written informed consent in accordance with the Declaration of Helsinki (World Medical Association 2001). All data collected has been stored in a database with password protection to which only researchers related to the NFT project have access. Anonymity was guaranteed.

Signal Acquisition

During the experiment, the participants sat in a room with a controlled environment—silent room with no light. The EEG signals were recorded according to the international 10–20 system (Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, P3, P4, T5, T6, O1, O2, Fz, Cz, and Pz), with a sampling frequency of 256 Hz. Feedback was from Cz channel, since this location is at the primary motor cortex and has been associated with sensory information processing over the sensorimotor area and provides a measurement of the activity in both hemispheres and in the frontal lobe (Mann et al. 1996; Pfurtscheller et al. 1999). The ground was located at the forehead and the reference was the average of left and right mastoids. The signals were amplified by a 24-channel system (Vertex 823 from Meditron Electomedicina Ltda, SP, Brazil) and were recorded by Somnium software platform (Cognitron, SP, Brazil) and NF module by Laseeb-ISR. The signals were filtered with an analog band-pass filter from 0.1 to 70 Hz in the amplifier and a digital band-pass filter from 4 to 30 Hz. Circuit impedance was kept below 10 kΩ for all electrodes. Subjects were asked to sit comfortably and then to remain as still as possible and also to avoid excessive blinking and abrupt movements.

Procedure

In the first session, all participants performed a 5 min NFT instruction to understand how to increase their defined threshold (initially set as 1.0, i.e., 100% ratio of the quotient between the mean IAB amplitude and the EEG total average amplitude, as shown in Eq. (1)) and achieve the test goals by interacting with the feedback provided on screen (further described in the 'Measurements' section). This was followed by the pre-tests (similar to the post-tests, both described in the 'Assessments' section), with instructions being given to clarify the study's purposes. The participants were asked to be as relaxed as possible and to concentrate on a specific sport task. If the feedback provided on screen was positive and the goals were being achieved, that would mean their strategy was working. If not, they were encouraged to find new strategies to achieve the goals. The pre and post-tests had the same interval of time for both the control and intervention groups, with the timeline of the NFT training sessions and respective performance test (pre and post) presented in Fig. 1.

Intervention Groups

The two-session-per-week and the three-session-per-week groups performed an instruction session and a pre-test before the 12 NFT sessions. At the end of completing all NFT sessions, a post-test was performed. Both pre and post-tests were carried out on the same day of the first and last training sessions, respectively. The NFT sessions consisted of 25 trials of 60 s each with 5 s rest in-between. The total NFT session time for each participant was 300 min in both intervention groups. Naturally, the participants who performed the most frequent protocol had more condensed NFT sessions than the subjects who performed the less frequent protocol. Although inhibiting mental self-talk seems to be one of the best strategies to achieve self-regulation of EEG activity during NFT (Harkness 2009; Hatfield et al. 2006; Hosseini and Norouzi 2017; Kamata et al. 2002; Wilson et al. 2006), participants were instructed only to concentrate on their sport activity as much as possible.

Control Group

The control group only performed pre and post-tests over a month and a half without the training sessions.

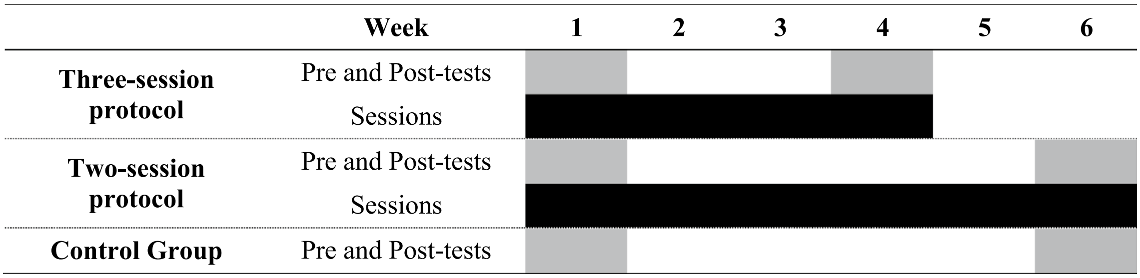
Measurements

The baseline recording in the pre-test consisted of four epochs of 30 s: two with the eyes open and two with the eyes closed during the resting period. Recordings of eyes open and closed in baseline provide data for the calculation of alpha desynchronization and synchronization respectively, enabling to determine frequency bands individually through amplitude band crossings (Klimesch 1999). The IAB information and their statistical comparisons between two NFT groups are summarized in Table S1 (see Supplementary Materials). Feedback is a determinant step for the protocol's success. Neural activity must be fed back by some parameter(s) and presented to the participant in a simple and direct representation of their value. In this study, the feedback parameter was the relative IAB amplitude calculated as in Eq. (1), where the numerator indicates the averaged amplitude in IAB, denominator indicates the averaged amplitude in 4–30 Hz, the LB is the lower frequency boundary (LB) of IAB, UB is the upper frequency boundary (UB) of IAB, and $X(k)$ is the frequency amplitude spectrum calculated by fast Fourier transformation (FFT) with a sliding window of 2 s that shifted every 125 ms. The frequency resolution was 0.5 Hz. Using the amplitude spectrum instead of the power spectrum prevents excessive skewing which results from squaring the amplitude, and thus increases statistical validity (Nan et al. 2017).

$$RelativeIAB\ amplitude = \frac{\frac{\sum_{k=LB}^{UB} X(k)}{UB-LB}}{\frac{\sum_{k=4}^{30} X(k)}{30-4}} \qquad (1)$$

The visual feedback display contains two objects: the first one in the centre and a second one in the lower left corner. These two objects change their shape and position, respectively, when the requirements are met.

The central object is a small white prism with a rhombus base (four-sided). As long as Goal 1 is being achieved, the number of sides of the base increases, progressively shaping and smoothing the white prism into a bigger purple sphere. If Goal 1 stops being achieved, the number of sides



	Week	1	2	3	4	5	6
Three-session protocol	Pre and Post-tests	▨			▨		
	Sessions	■	■	■	■		
Two-session protocol	Pre and Post-tests	▨					▨
	Sessions	■	■	■	■	■	■
Control Group	Pre and Post-tests	▨					▨

Fig. 1 Timeline of the NFT training sessions and respective performance tests (pre and post-tests)

progressively decreases back to the initial rhombus shape, with its colour fading back to white and its size diminishing.

The second object is a cube whose position on screen is related to the period of time that Goal 1 kept being achieved continuously. If it happens for more than a predefined period of time (2 s), Goal 2 is accomplished and the cube moves upwards until Goal 1 stops being achieved. If that happens, it will start moving downwards back to the initial position unless Goal 2 is achieved again. Therefore, the participant's task is to move the cube upwards as much as possible (Rodrigues et al. 2010).

As previously stated, the feedback threshold's ratio was set to 1.0 in the first session, and it was adjusted according to the percentage of time in which the feedback parameter was above the threshold in each session. If this percentage exceeded 60%, the threshold's ratio would be increased by 0.1 in the next session. In contrast, if the percentage was below 20%, the threshold's ratio would be decreased by 0.1 in the next session (Nan et al. 2013).

Assessments

Digit Span

Participants had to recall a random sequence of numbers in the correct order, starting with 2 digits and ending with 10 digits with a digit speed of 2 s between each one. Participants were asked to introduce the digits in the order by which they appeared (YuLeung To et al. 2016). The longest correct sequences of digits the participants achieved was taken as the participant's score.

N‑Back Test

During the N-Back test the individuals were required to monitor a series of numbers and identify if the current one was the same that was presented n trials before, with $n = 2$. Twenty-two trials were performed, which resulted in 20 answers. Each digit was shown for a maximum of 2 s during which the participant could answer, and there was an interval of 2 s between trials (Kirchner 1958). The accuracy was used as the participants' score in this test.

Oddball

The oddball test is used to evaluate the attention of the subjects. In this test, different geometrical forms appear (a circle, an octagon and a square) and the volunteers were instructed to click only if the circle appears. The test consisted of 50 trials, where the images appeared for 0.5 s with an interval of 0.5 s. A decoy rate of 40% was defined (Debener et al. 2005). The accuracy was used as the participants' score in this test.

Transfer Session

A 10-min session without any visual feedback was performed to assess the ability of participants to achieve their defined threshold by themselves (Rockstroh et al. 1993; Siniatchkin et al. 2000). In this performance test, electrical activity was recorded at Cz and the participants were seated in front of a turned-off screen. Participants were instructed to try and reach their defined threshold but without any feedback (only the researcher had access to the monitor that indicated whether or not the participants were working within the IAB range) while maintaining their eyes open. The only request made to the participants was to concentrate on their sport activity as much as possible.

Data Analysis

Data was analysed with SPSS software for Windows version 25.0 (SPSS Inc., Chicago, IL). Statistical significance was set at $p < 0.05$ for all tests.

Regarding the EEG analyses, we firstly conducted linear regression analysis on the mean relative IAB amplitude across all participants in each NFT group, in order to examine the average change trend over all 12 NFT sessions. Secondly, considering that Shapiro–Wilk test showed violation of normal distribution in the relative IAB amplitude in the first and last sessions in each NFT group, Wilcoxon signed test was applied to compare the difference of the relative IAB amplitude between the first and last NFT sessions. Thirdly, regarding the relative IAB amplitude in transfer session, normality was verified in pre and post-tests for all groups. Therefore, mixed-design repeated-measures analysis of variance (ANOVA) with Time (pre, post) as within-subject factor and Group (two-session protocol, three-session protocol, control) as between-subject factor was conducted.

For the cognitive performance analyses, given that the performances in all three cognitive tasks in pre- and post-tests were not normally distributed examined by Shapiro–Wilk test, we utilized Wilcoxon signed test to examine the cognitive difference between pre- and post-tests in each group, separately.

Furthermore, Spearman correlation test (one-tailed) was conducted to examine whether positive correlation existed between cognitive performance change and NF learning. The NF learning was quantified by the linear regression slope where the number of sessions was taken as the independent variable and the relative IAB amplitude as the dependent variable, indicating the learning speed across the whole training time (Kober et al. 2017; Nan et al. 2012).

Results

EEG Results

Figure 2 presents the mean relative IAB amplitude across all participants in each NFT group over 12 NFT sessions. Linear regression analysis showed that the mean relative IAB amplitude showed significant positive linear slope in the three sessions per week protocol group (slope = 0.013, $p = 0.02$, $R^2 = 0.431$), which was not the case for the two sessions per week protocol group (slope = 0.002, $p = 0.65$, $R^2 = 0.022$). Furthermore, Wilcoxon signed test showed that the three-session protocol group had significant differences in the relative IAB amplitude between Session 1 and Session 12 ($Z = -3.182$; $p < 0.001$), suggesting significantly increased IAB in Session 12 compared to Session 1 with three sessions of NFT per week. On the contrary, no significant difference was found in IAB between Session 1 and Session 12 in the two-session protocol group ($Z = -0.228$; $p = 0.820$). The above results suggested that NFT with three sessions per week could successfully increase the relative IAB amplitude during training sessions rather than NFT with two sessions per week.

The relative IAB amplitude in the transfer sessions in each group (the detailed value can be found in Table S2 in supplementary materials) is presented in Fig. 3. By mixed-design repeated-measures ANOVA, Group had significant main effect ($F(2,42) = 29.84$, $p < 0.001$, partial $\eta^2 = 0.587$). However, neither significant main effect of Time ($F(1,42) = 0.54$, $p = 0.466$, partial $\eta^2 = 0.013$) nor significant interaction between Time and Group ($F(2,42) = 0.447$, $p = 0.643$, partial $\eta^2 = 0.021$) was observed. Planned pairwise comparisons between pre- and post-tests in each group also showed no significant difference ($p > 0.05$). The above results suggested no significant difference in IAB changes in transfer session from pre and post-tests between groups.

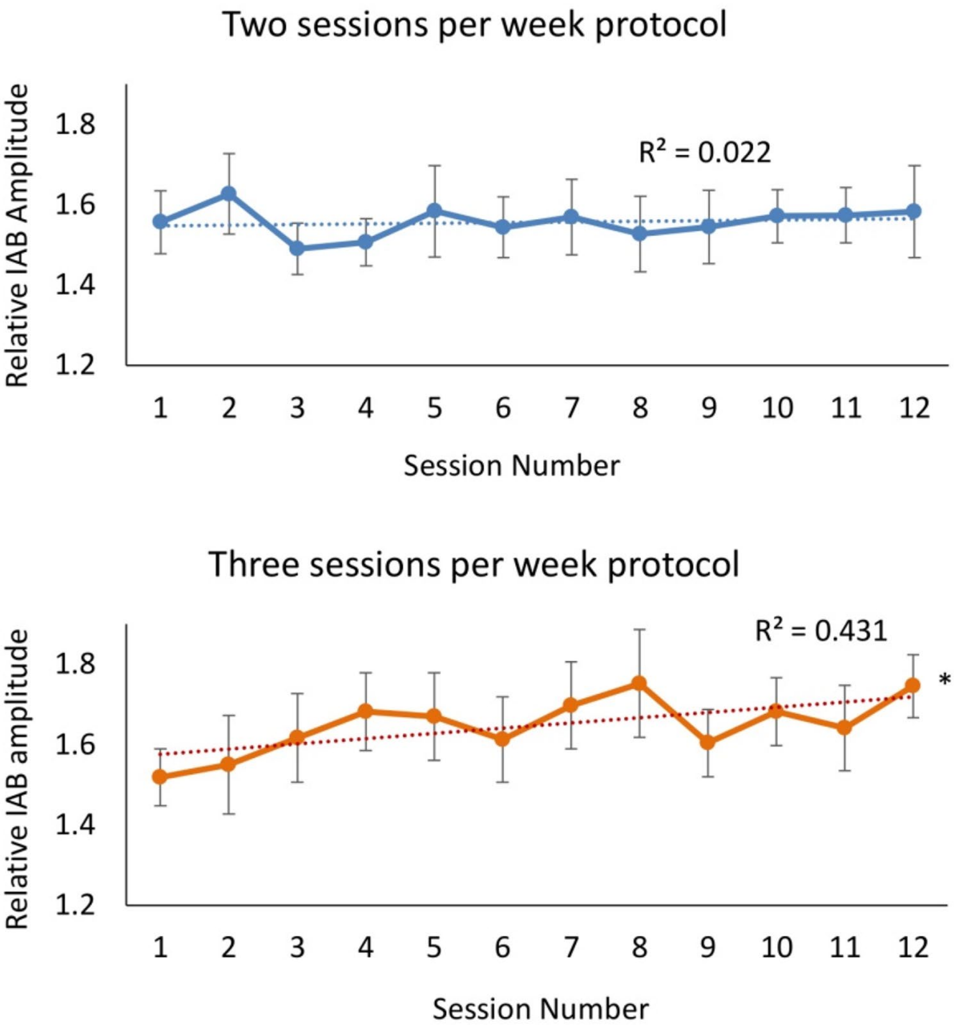


Fig. 2 Mean relative IAB amplitude in each NFT group over 12 sessions. Solid line and dashed lines represent mean relative IAB amplitude in each session and its slope over sessions. Error bars indicate the SEM. Significant regression slope and significant increase from Session 1 to Session 12 can be found in the three sessions per week protocol group (symbolised by*)

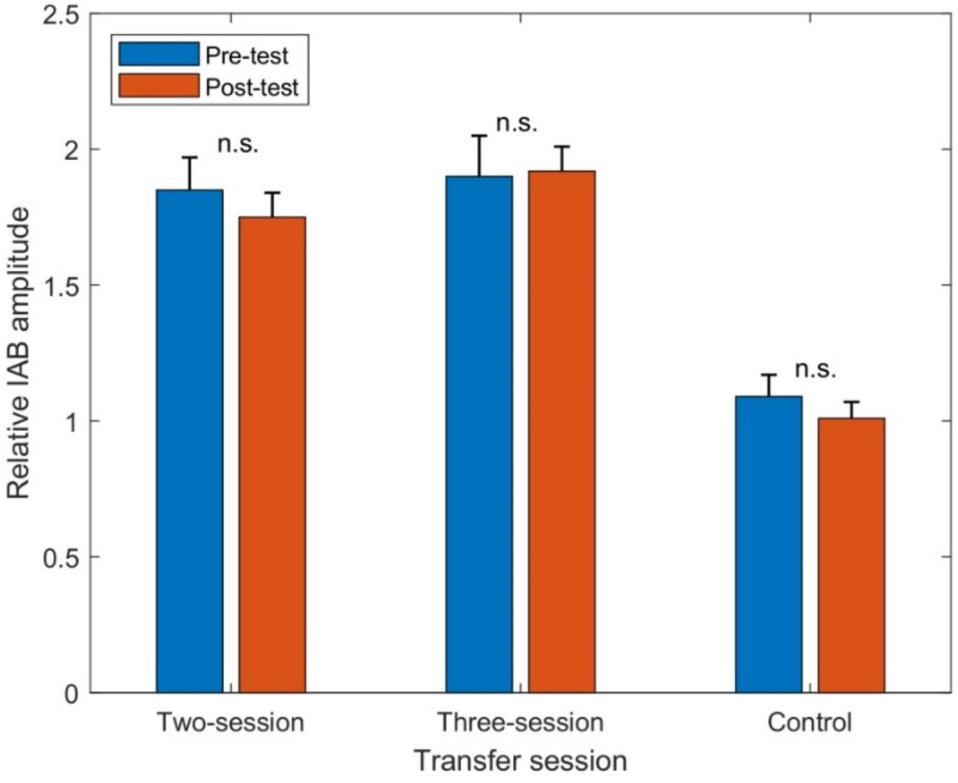


Fig. 3 The relative IAB amplitude in the transfer sessions in pre- and post-tests. The error bars indicate SEM. *n.s.* non-significant

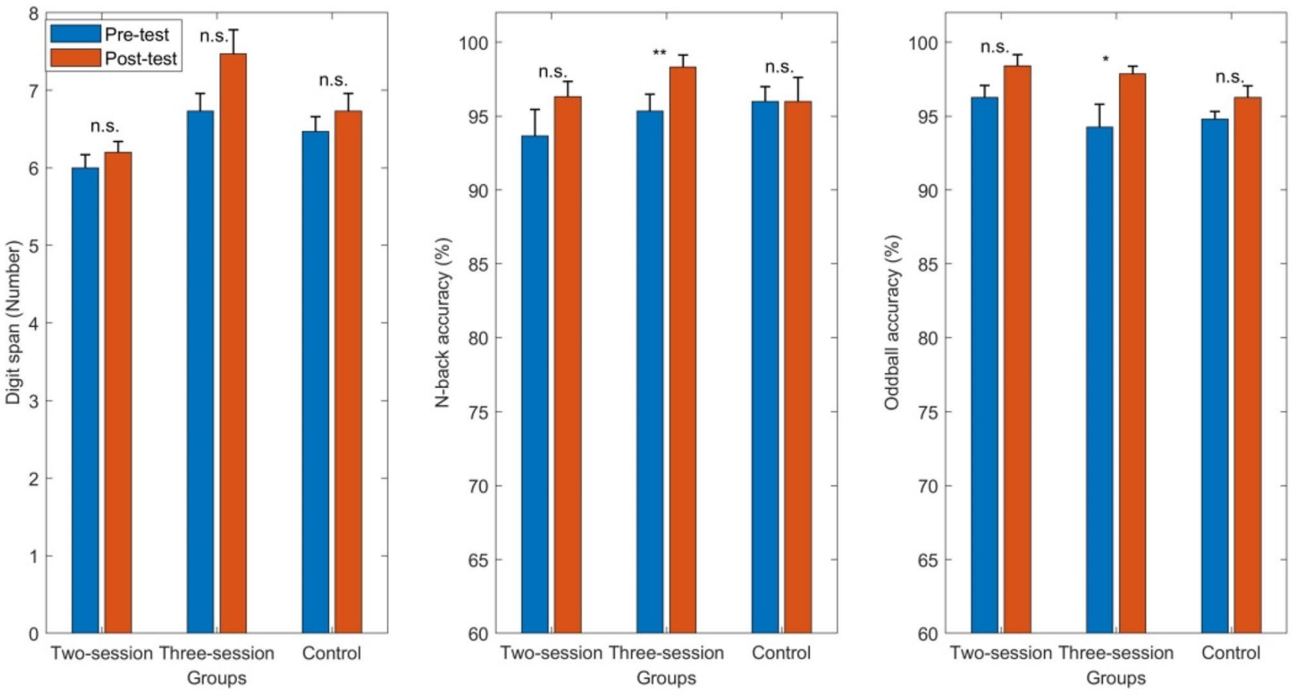


Fig. 4 The cognitive performance in pre- and post-tests for all groups. The error bars indicate SEM. $**p < 0.01$; $*p < 0.05$; *n.s.* non-significant

Cognitive Performance

Figure 4 shows the cognitive performance in pre- and post-tests for all groups (the detailed value can be found in Table S3 in supplementary materials). In the three-session protocol group, the difference between pre- and post-tests in digit span was marginally significant ($Z = -1.895$; $p = 0.058$), while the differences between pre and post-tests were significant for both N-back ($Z = -2.714$; $p = 0.007$) and oddball ($Z = -2.195$; $p = 0.028$). In the two-session protocol group, there was no significant difference between pre and post-tests for either digit span ($Z = -1$; $p = 0.317$), N-back ($Z = -1.469$; $p = 0.142$), or oddball ($Z = -1.906$; $p = 0.057$). Likewise, the control group had no significant difference between pre and post-tests in digit span ($Z = -1.414$; $p = 0.157$), N-back ($Z = -0.423$; $p = 0.666$), or oddball ($Z = -1.889$; $p = 0.059$).

Furthermore, one-tailed Spearman correlation test showed a positive correlation between the NF learning and the oddball performance change in the three-session-per-week protocol group ($r = 0.524$, $p = 0.023$), which was not case for the two-session-per-week protocol group (see Fig. 5).

Discussion

The aim of the study was to examine NFT session frequency effects on both IAB activity and specific cognitive performance in athletes. The IAB activity was evaluated during NFT sessions and transfer sessions, while the cognitive performance was evaluated with three different tasks.

Our results demonstrated that the three-session-per-week group had better EEG results than the two-session-per-week group, in the relative IAB amplitudes during NFT, evidenced by the linear slope over all 12 sessions (Fig. 2) as well as the changes between Session 1 and Session 12. The above findings lend preliminary support that the relative IAB amplitude change will be different between both protocols, meaning that the frequency of sessions contributes to the effectiveness of training and the most condensed training lend to a better NF learning performance of the relative IAB amplitude.

Likewise, the three-session-per-week group had better cognitive performance results than the two-session-per-week group. More specifically, the results for the N-back and oddball cognitive performance tests revealed significant improvements over time within the group with three sessions per week. The findings suggested that cognitive enhancement showed better results in the more condensed protocol, which is not the case in the less condensed one. Importantly, we found the significant positive correlation

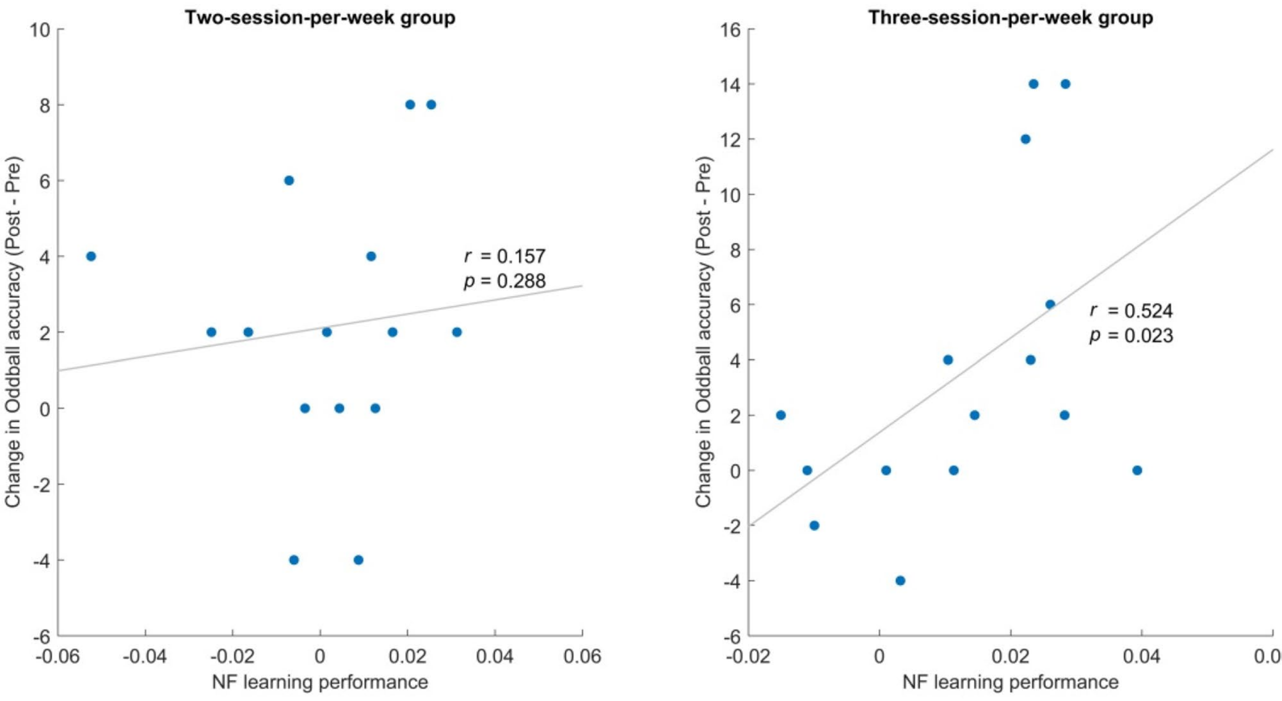


Fig. 5 The relationship between NF learning performance and oddball accuracy change (Post–Pre) in each NFT group

between the NF learning and the change of oddball performance, proving that a link exists between the learning effects of NFT and this specific behaviour change by NFT (Nan et al. 2012).

Although there are some studies with the same number of sessions per week, characteristics such as band or site are not verified and therefore any comparison is relative. Considering that one of the major gaps of NFT are the protocols applied (because of diversification—duration, site, band, frequency), the results were compared with studies that increased the alpha amplitude and applied two to three sessions per week (Dekker et al. 2014; Harkness, 2009; Rostami et al. 2012; Strizhkova et al. 2014; Ziółkowski et al. 2012). Dekker and collaborators (2014) developed a study that also shows significant improvements in alpha amplitude over time (in the intervention group) but, contrary to our study, when comparing the intervention group vs the control group, the differences are not significant (Dekker et al. 2014). A case study was performed with an elite shooting athlete where the increase of accuracy was verified. However, having only one subject did not allow to understand whether the effects were due to NFT, task practice, or both (Harkness 2009). In the same line of research, Rostami et al. (2012) studied the effect of NFT in rifle shooters' performance and found that the intervention group had significant results in shooting after a 15-session period (three sessions/week) against a non-NFT group, that is, NFT proved to be useful in improving accuracy in shooting when increasing theta, alpha and SMR while high beta was inhibited (Rostami et al. 2012). A two-session program performed by a single javelin thrower led to an increase in reaction speed (Ziółkowski et al. 2012).

The results found are in agreement with what was expected, except for the two-session-per-week protocol. The conditions were very homogeneous (the sessions were held in exactly the same place and all students belonged to the same faculty) and student-athletes had a very similar academic routine. One of the possible explanations for the less frequent protocol to be worse than the most frequent protocol could be the less condensed training schedule, which makes it difficult to improve the relative IAB amplitude over sessions. In addition, NFT transfer effects on EEG without NFT session have been rarely examined in the previous work. Our results showed no significant difference between pre- and post-tests in three-session-per-week protocol group compared to other two groups, suggesting that successful NFT learning during NFT sessions may not link to the state when NFT was not presented. This is also reasonable since achieving immediate regulation ability during NFT has been considered as the nature of NFT learning rather than the offline state without NFT (Witteet al. 2018). What is more, the significant correlation between NFT learning and oddball performance change further suggested the importance of NFT learning during NFT sessions rather than the transfer session without NFT.

The main strength of the study and what makes it so important is that it answers one of the major limitations pointed out by the scientific community about the ideal duration and number of sessions per week for NF learning in neural bands (Dekker et al. 2014; Maszczyk et al. 2018; Mirifar et al. 2017; Perry et al. 2011; Xiang et al. 2018), demonstrating that a more condensed protocol is more effective than a less condensed protocol. However, we do not know if more than three (e.g. four or five) sessions per week would be better than three. The training individualization was also considered (IAB was used instead of the fixed alpha band) (Klimesch 1999). A control group was used to exclude the task practice effect. These last two arguments are two factors of protocol robustness (Mirifar et al. 2017; Xiang et al. 2018). The point of this comparison between protocols is to provide potential guidance for future investigations.

There are some limitations that should be considered. Firstly, the mental strategies were not recorded. Future work would include a questionnaire or scale to better understand what strategies athletes are using during NFT and which mental strategies are helpful to enhance NF learning of training frequency band activity (Gruzelier 2014). Furthermore, there was a large diversity of sports. Considering the different brain areas required in different activities and skills, the specificity of each of those sports might have influenced the results. The present study should therefore be considered exploratory. Additionally, only cognitive laboratory tests were performed whereas behavioral changes were not verified in the sports context, so it is imperative to not generalize the results.

It can be concluded that the three-session protocol is more effective than the two-session protocol in enhancement of individual alpha during NFT and specific cognitive performance in student athletes, suggesting that more effective NFT results can be achieved with more condensed protocols. Meanwhile, the more condensed protocol required less time (4 weeks vs 6 weeks). Future research should replicate the three-session protocol based on a pre-test and post-test associated to the sport to better understand how the increased alpha contributes to a better sporting performance. Likewise, it would be necessary to compare with a more intensive training protocol (e.g., four or five sessions per week). Additionally, stronger conclusions could be drawn in future studies with active control conditions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10484-021-09505-3.

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Author contributions CD: Conceptualization, Visualization, Writing-Original draft preparation and Investigation. MP: Data curation and Methodology. PP: Writing-Original draft preparation and Software WN: Writing-Reviewing and Editing. AR: Writing-Reviewing and Supervision. JGP: Writing-Reviewing and Supervision.

Compliance with Ethical Standards

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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