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Abstract

Frontal midline theta power (FMT) has been associated with superior rifle shooting performance. Our experiment examined whether electroencephalographic-based training could increase FMT, shooting performance and attentional focus in highly-trained/elite biathletes. Participants (n = 28; age, *M* = 21.7, *SD* = 2.3) were assigned to a control group or an intervention group (with 3 h of neurofeedback training). FMT increased from baseline during the neurofeedback training sessions ($p \leq 0.05$). However, there were no group × pre-post training (test) interactions for FMT or shooting performance ($p > 0.05$). There was a small group × test effect for attentional focus ($p = 0.07$; $\eta_p^2 = 0.12$), indicating a potential benefit of neurofeedback training. Superior shooters were more proficient at increasing FMT during neurofeedback training, but this did not translate to greater improvements in shooting performance. Our findings suggest that the effects of neurofeedback training are transient and do not necessarily benefit performance.

Keywords: biathlon, brain training, EEG, rifle shooting, winter sport

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The ability to actively process relevant information, known as attentional focus, is important in precision aiming tasks such as target shooting (Luchsinger et al., 2016; Doppelmayr et al., 2008; Baumeister et al., 2008). The winter sport of biathlon, which combines the precision element of rifle shooting with the physical challenge of cross-country (XC) skiing, requires high levels of attentional focus directly after periods of high-intensity exercise. A biathlon race involves 3 or 5 skiing bouts interspersed with 2 or 4 shooting bouts in alternating prone and standing positions, with targets situated 50 m from the shooting mats. In sprint races, skiing speed appears to be most decisive for overall performance (Luchsinger et al., 2018), whereas the shooting element is particularly important in individual (Luchsinger et al., 2019; Björklund & Laaksonen, 2022), pursuit (Luchsinger et al., 2020; Björklund et al., 2022) and mass-start (Björklund et al., 2022) races. Therefore, interventions to improve shooting accuracy in elite biathletes have the potential to significantly improve competitive performance. However, this has only been investigated in two previous studies (Laaksonen et al., 2011; Groslambert et al., 2003).

Research has shown that frontal midline theta power (FMT), which is a specific form of cortical activation at frequencies between 4–7 Hz (Ishihara & Yoshi, 1966), is associated with greater attentional focus (Baumeister et al., 2008). Dopplemayr et al. (2008) found that FMT was higher in the interval between 1–0.5 s before trigger-pull in expert compared to novice rifle shooters, and greater FMT was associated with superior shooting performances in the experts. Similarly, Luchsinger et al. (2016) found that biathletes (i.e., expert shooters) had higher FMT from 2 s before to 1 s after trigger-pull, as well as superior shooting performance, compared to cross-country skiers (i.e., novice shooters). Increasing cardiovascular load up to 100% of maximal oxygen uptake has been shown to have a detrimental effect on standing rifle shooting performance, due to reductions in external focus (Vickers & Williams, 2007) and rifle stability (Hoffman, 1992). In addition, Gallicchio et al. (2016) demonstrated that FMT was significantly lower when shooting immediately after 3 min of cycling exercise at 90% of heart rate (HR) maximum compared to after no prior exercise. However, in both rest and exercise conditions FMT peaked in the last 250 ms before the shot was taken and shooting performance was maintained. This indicates that increasing FMT just prior to a shot may compensate for any overall reductions in FMT associated with cardiovascular load. As such, training biathletes to increase their FMT before pulling the trigger may be an effective method for improving shooting performance in the context of a biathlon race.

Neurofeedback training is a technique that has been used to help regulate specific brain activity patterns (Xiang et al., 2018). Skinner et al. (1963) demonstrated that organisms can learn to increase behaviors connected with positive feedback and decrease behaviors associated with negative feedback. Applying this principle, neurofeedback training can reinforce brain activity patterns for a given task by providing positive or negative feedback in either audio or visual forms, using real-time brain activity from electroencephalogram (EEG) measurements (Hammond, 2007). There is encouraging evidence for the benefits of neurofeedback training in clinical populations. For example, EEG neurofeedback has been shown to alter EEG power and decrease symptoms of attention deficit hyperactivity disorder (ADHD), depression and autism (Omejc et al., 2019). A recent meta-analysis of 10 studies concluded that neurofeedback training can change EEG power and improve sports performance (Xiang et al., 2018). For example, Cheng et al. (2015a) demonstrated that approximately 4 h of neurofeedback training improved both sensorimotor rhythm (SMR) power (12–15 Hz) and putting performance in experienced golfers compared to a control group. Similar performance benefits have been revealed after 15 h and 2.5 h of SMR neurofeedback training for rifle and pistol shooting, respectively (Gong et al. 2020; Rostami et al. 2012). However, neither of these studies recorded

EEG activity during the pre- and post-intervention shooting tests. Outside of sport, 30 min of increased FMT neurofeedback training was associated with improved motor performance (finger tapping) and an enhanced perception of a flow state (Eschmann et al., 2022). Together, the existing literature provides encouraging evidence that neurofeedback training could be applied to augment FMT and rifle shooting accuracy in trained biathletes.

Not all participants experience benefits of neurofeedback training. For example, previous studies have shown that 25% (Enriquez-Geppert et al., 2014) and 37% (Lubar et al., 1995) of participants were unable to change theta power after 5 and 33.3 training hours, respectively. Features that distinguish responders and non-responders to neurofeedback interventions are not well understood. Therefore, in addition to examining the effects of FMT neurofeedback training on shooting performance at a group level, analyses of inter-individual variability in training responses are also worthy of investigation.

Purpose of the Present Study

The purpose of the present study was to identify whether neurofeedback training would lead to increased FMT and improved rifle shooting performance and attentional focus in experienced biathletes. Additionally, we explored the differences in individual responses to the training intervention, to shed light on any features that distinguish relative “responders” from “non-responders”. We hypothesized that using neurofeedback training to target FMT with highly-trained and elite biathletes (McKay et al., 2022) would increase their FMT, shooting accuracy and self-reported attentional focus during a precision shooting task and a simulated biathlon performance task. Secondly, inter-individual variability was expected in FMT responsiveness after the neurofeedback intervention, with relative responders hypothesized to improve their shooting accuracy and attentional focus to a greater degree than non-responders.

Method

Participants

Twenty-eight highly-trained and elite biathletes (Table 1) competing at national and/or international levels were recruited through collaboration with the Swedish Biathlon Federation. The participants were pair-matched based on their best shooting test scores, which were provided by national team coaches and are derived from a standardized test of 30 prone and 30 standing shots measured at rest several times per year. Participants from each pair were randomly assigned to either a neurofeedback training group (NFB) or a control group (CON). G*Power 3.1 power calculation software (Faul et al., 2009) indicated that by adopting an alpha of 0.05 and a sample size of 28, the experiment was powered at 0.80 to detect a between-within interaction for effect sizes exceeding $f = 0.27$ (i.e., medium-size effects) by 2 × 2 mixed-model ANOVA (Cohen, 1992). Previous sport-based neurofeedback studies adopting 2 × 2 mixed-model designs reported significant and medium-sized interaction effects for frontal midline cortical activity ($\eta_p^2 = .33$; Ring et al., 2015) and for performance ($\eta_p^2 = .26$; Cheng et al., 2015a). Accordingly, if similar effects were to emerge, our sample was adequately powered to detect them. Participants were fully informed about the nature of the study before providing written consent to participate. The study was conducted according to the Declaration of Helsinki and was approved by the Swedish ethical review authority (ref. XXXX-XXXXX).

Design

A mixed-multifactorial design was adopted for the study. The primary within-participant factor was test, which had 2 levels (pre-test vs. post-test). All participants completed pre- and post-tests, hereafter referred to as the test phase of the experiment, which included the assessment of precision shooting and simulated biathlon performance. The primary between-participant factor was group, which also had two levels (NFB vs. CON). Between the pre- and post-tests, the NFB group completed 6 neurofeedback training sessions (S1–S6), each separated by *M* = 2, *SD* = 2 days, hereafter referred to as the training phase of the experiment. Each training session consisted of 10 × 3-min blocks of neurofeedback training, which aimed to increase the participants' FMT whilst dry-firing their rifle in a seated position. Members of CON completed no neurofeedback training. All testing and training took place during pre-season (July to September). Participants attended all testing sessions having had no caffeine or nicotine for at least 3 h, no alcohol for 24 h, at least 7 h of sleep the previous night and no high-intensity training on the day of the test.

Procedures

Test Phase

The pre- and post-tests were completed outdoors on an international-standard biathlon shooting range (temperature, *M* = 16.1, *SD* = 4.1ºC; wind speed, *M* = 0.47, *SD* = 0.46 m/s; Kestrel 2000 wind meter, Claygate, England). On initial arrival at the arena the participants were briefed, provided their consent to participate, were weighed, put on a HR monitor (Equivital Life Monitor: eq02+, New York, US) and prepared their rifle with standardized .22-long rifle ammunition (Lapua Center X, Lapua, Finland). Ammunition from the same batch was used by both participants within each matched pair during the pre- and post-tests.

The BIA1200 biathlon target system (Megalink, Verpetveien, Norway), placed at a 50-m distance, was used for all shooting tests. Before the start of the tests 10 shots were fired in a prone position according to standard procedure, allowing rifle sights to be calibrated using immediate feedback from the targeting system. EEG electrodes (Ambu NF-00-S/12, Ballerup, Denmark) were then affixed at the Fz (recording electrode) and FPz (ground electrode) sites on the scalp, and at the left or right mastoid (reference electrode) for right- and left-handed participants, respectively. The electrodes were secured using a nylon cap (Electro-cap International Inc, Eaton, USA) fitted according to the 10–20 system (Jasper, 1958) and were connected to a DC amplifier (Brainquiry, PET 4, Nijmegen, Netherlands). The EEG amplifier was secured on the participant's upper back using a wearable vest, to limit obstruction when shooting and to reduce movement of the EEG electrodes. Illustrations of the field-testing setup are presented in Figure 1, with the EEG electrodes and nylon cap pictured in Figure 1A.

The testing phase included a precision shooting test at rest and a simulated biathlon performance test. The precision shooting test comprised 10 shots in a prone position followed by 10 shots in a standing position. Participants were instructed to fire as close to the center of the target as possible with each shot, to achieve the highest possible score (see the **Measures** section, below). Immediate feedback was available from the targeting system throughout the test (Figure 1B). To simulate time pressure, a maximum of 90 s was allocated to complete each set of 10 shots. Within this time frame the participants were required to reload their rifles after 5 shots, at which time the experimenter announced how much time was remaining. Each set of 10 shots was separated by a short break, no more than 1 min in duration, while data was saved, the target system was re-set, and the rifle was reloaded.

The EEG equipment was removed after the precision shooting test and participants prepared for the simulated performance test, which comprised 4 min of double poling on a ski ergometer (Concept2 SkiErg, Morrisville, USA; Figure 1C) followed by 5 shots at the shooting range, repeated for 4 cycles without a break and alternating prone and standing shooting (i.e., prone for shooting blocks 1 and 3, standing for shooting blocks 2 and 4). Participants wore their own XC ski boots throughout the simulated performance test, which were clipped into a standardized position using XC ski bindings (Rottefella, Klockarstua, Norway; Salomon, Annecy, France) that were fixed to the ground. The drag factor on the ski ergometer was set to 100 and 120 for the women and men, respectively, and a standardized 5-min incremental warm-up was completed prior to the start of the test at intensities from zones 1–4 (Karlsson et al., 2021). A 2-min rest separated the warm-up and the simulated performance test, in which the 4 × 4-min double-poling intervals were completed at zone 3 intensity (~ 90% of maximal HR; blood lactate concentration 4.0–7.0 $\text{mmol}\cdot\text{L}^{-1}$; ~ 16 rating of perceived exertion, RPE). The

RPE (6–20 Borg scale) and a perceived intensity rating (i.e., zone 1–4) were recorded after each minute of the first 4-min interval and participants were instructed to adjust their pace closer to zone 3 if required. In the three subsequent 4-min intervals, RPE and perceived intensity were monitored every 2 min to ensure zone 3 intensity was maintained. After each interval participants collected their rifle from a rack positioned 1 m from the ski ergometer, placed the rifle on their back and stepped onto the shooting mat placed 3 m from the ski ergometer. Five shots were fired at the targets successively, as quickly and accurately as possible, to simulate a competition scenario (Figure 1D). No feedback was provided during shooting, but the participant could look at the target system on leaving the shooting range, as they returned to the ski ergometer, to assess the accuracy of their 5 shots. Before starting the next 4-min double poling interval, the rifle was returned to the rack.

Matched pairs of participants completed their pre- and post-tests on the same day and within 2 h of each other, to standardize the weather conditions. The post-test was completed at least 13 days after the pre-test (*M* = 17, *SD* = 3 days), and always within 2 h of the pre-test time to standardize for circadian rhythm. The only difference from the pre-test was that the participants were informed of their average power output (PO) during each minute of the 4 × 4-min double poling intervals and were instructed to replicate that PO as closely as possible. If a participant exceeded a RPE of 18 or perceived their intensity to be above zone 3, they were instructed to decrease their PO to replicate a zone 3 intensity, similar to the pre-test.

Training Phase

S1–S6 took place indoors at the biathlon arena and included 30 minutes of auditory neurofeedback training per session separated into 10 × 3-min intervals interspersed with 1 min of rest. An active electrode attached to a DC amplifier (Brainquiry PET 4) was connected to the Fz site of the scalp with the reference electrode attached to the right or left mastoid for right- or left-handed participants, respectively. The ground electrode was attached to the middle of the forehead, at the FPz site. A further active electrode was placed over the orbicularis oculi muscle of the right or left eye for right- or left-handed participants, respectively, to remove eye-blink artefacts. Once set up, baseline EEG theta power was measured and averaged (see the ***FMT*** section, below). Having established individual baselines, the experimenter manually set the threshold for silencing the neurofeedback tone (a 10%, 20% and 30% increase from baseline in S1–S2, S3–S4 and S5–S6, respectively) in the neurofeedback software.

Feedback was provided at the Fz site based on previous research associating greater FMT in the 2 s preceding trigger-pull with expertise and superior shooting performance (Luchsinger et al., 2016). FMT (4–7 Hz) was extracted from the EEG signal and fed back to participants in the form of an auditory tone (Ring et al., 2015). Importantly, the tone was programmed to vary in pitch based on the level of FMT and to silence completely when FMT was increased from baseline by the required amount (i.e., 10–30%) for a minimum of 0.4 s. In addition to increasing FMT, the system also required < 10 μV of 50 Hz activity in the signal (i.e., low impedance) and the absence of eye blinks, as detected by the electrode placed adjacent to the right or left eye for right- or left-handers for the tone to silence. Eye blinks were detected as > 90 μV of 1–10 Hz activity at the eye electrode. These control features helped ensure the signal was being shaped by cognition and was not contaminated by electrical, muscular or eye-blink artefacts (Ring et al., 2015).

Before the first training session began participants were familiarized with the auditory feedback when their FMT was below and above the targeted threshold. During the 10 × 3-min training blocks participants were instructed to replicate their shooting process by aiming their sights and trying to silence the auditory tone with their mind. To encourage participants to develop their own techniques via operant conditioning, where the tone silence served as the reward, we refrained from providing explicit instructions or strategies about how to silence the tone. This approach is consistent with previous neurofeedback research (Cooke et al., 2018;

Ring et al., 2015). Only when the participants had silenced the auditory tone and felt they were ready to shoot would they pull the trigger and dry-fire at a paper target, which was placed 5 m away from the participant's seated position. Participants were encouraged to find a technique that helped them to increase their FMT, therefore silencing the auditory tone for longer periods of time and enabling them to perform successive dry-fire shots. These instructions were designed to help aid an association between increased FMT and trigger-pull.

FMT Recording

EEG activity was recorded from the frontal midline (i.e., Fz) site. On all occasions recording sites were prepared by applying exfoliant gel (Nuprep, Aurora, USA) with a cotton bud, cleaning the site with alcohol wipes (Medisave, Weymouth, England) and applying conductive gel (Signagel, Parker) to ensure that electrode impedances were below 10 kΩ. The signals were digitized at 24-bit resolution (Brainquiry) and transmitted via Bluetooth at a sampling rate of 200 Hz to a computer running Bioexplorer (Cyberevolution) software. We employed a Butterworth infinite impulse response (6th order) bandpass filter at 4–7 Hz to extract FMT. Recordings during the precision shooting test commenced at the instructor's prompt and ended on completion of the 10th shot. The prone and standing precision tests were recorded separately. Recordings during the training phase started and ended at the onset and offset of each 3-min training block. FMT was averaged over the entire recording epochs. We also obtained baseline recordings immediately before the precision shooting pre- and post-tests, and at the start of S1–S6. For each baseline measure, participants were asked to assume a seated position and fixate on a target with a relaxed focus for a period of 6 s. This process was repeated 5 times, each separated by 30 s, and the average of those 5 recordings was used to establish baseline FMT for that test (pre-test, post-test) or training session (S1–S6).

Measures

Precision Shooting Test

Prone and standing shooting precision were assessed by summing the scores from the 10 shots in each position, with each shot scored from 0 (i.e., outside the outer ring) to 10.9 (i.e., the center of the target). Results therefore ranged from 0 (least accurate) to 109 (most accurate) in each position. Immediately after the 20 shots, participants rated how focused they felt during the test using a 1–10 Likert scale (1 = ‘not focused at all’; 10 = ‘completely focused’).

Simulated Performance Test

Average PO (in W) and RPE were recorded every minute during the first 4-min double-poling interval and every second minute in subsequent intervals. HR data was recorded every 5 s during the double-poling skiing bouts and averaged for each 4-min interval. Two measurements of shooting performance were calculated during the simulated performance test, a target hit score and an accuracy score. The target hit score was determined from the number of hits and misses and with a total of 20 shots, ranged from 0–20 (on the electronic target system a hit is classified as a score above 8.2 in the prone position and above 3.7 in the standing position). The accuracy score was calculated by summing the specific scores for the 20 shots, which ranged from 0–10.9 per shot, to give a total score of between 0 and 218. Total shooting time was calculated by summing the times for each shooting phase, which started when the participant stepped onto the shooting mat and stopped when they stepped off the shooting mat. This time was measured manually using a stopwatch. At the end of the simulated performance test, participants rated how focused they felt overall during the shooting phases of the performance test using a 1–10 Likert scale (1 = ‘not focused at all’; 10 = ‘completely focused’).

FMT

Baseline-normalized change scores were computed using the following formula:

$$\text{Fz Theta Power percent change} = \frac{(\text{Fz theta power task} - \text{Fz theta power baseline})}{\text{Fz theta power baseline}} * 100$$

Positive scores indicate an increase in FMT from baseline to task, while negative scores indicate a decrease in FMT from baseline to task.

Statistical Analysis

Independent sample t-tests were used to compare the descriptive data for the matched participants in the NFB and CON groups.

To examine the effectiveness of the neurofeedback training intervention, a one-sample t-test was performed on the FMT percent change for each 3-min block. This ascertained whether the increase in FMT was significantly greater than zero. Furthermore, a two-way ANOVA was performed on the FMT percent changes to examine whether the ability to increase FMT evolved across training sessions (S1–S6) and/or blocks (10 × 3-min).

To examine the effects of the neurofeedback intervention on FMT, shooting performance and attentional focus measures obtained in the test phase of the experiment, a series of two group (NFB, CON) × two test (pre-test, post-test) ANOVAs were performed. Significant ANOVA effects were probed by paired-sample t-tests and one-sample t-tests (in the case of FMT) to establish whether changes from baseline to the precision shooting task were significant.

As a control analysis, the exercise measures obtained during the performance test (i.e., PO, HR and RPE) were subjected to two group (NFB, CON) × two test (pre-test, post-test) × four exercise blocks (each of the 4 × 4-min bouts on the ski ergometer) ANOVAs. These analyses tested our assumption that the two groups would exercise at similar intensities during both the pre- and post-tests.

To achieve our secondary aim of investigating inter-individual variability in response to the neurofeedback training, we inspected FMT during the intervention phase for each individual in the NFB group. Specifically, we considered the number of training blocks where participants increased FMT from baseline, and the magnitude of the change in FMT from baseline. This allowed us to identify relative responders and non-responders to the intervention. Individuals were defined as responders if they increased their FMT from baseline in > 75% of the training blocks and if their *M* increase in FMT was > 10%. They were defined as non-responders if they increased their FMT in ≤ 50% of the training blocks and if their *M* increase in FMT was < 5%. Participants that did not fall into either category were omitted from the responder or non-responder phase of analysis. We then performed a series of two group (responder, non-responder) × two test (pre-test, post-test) ANOVAs on FMT and performance measures obtained in the test phase of the experiment. These analyses allowed us to establish any features that distinguished neurofeedback responders from their less responsive counterparts.

Statistical analyses were performed using SPSS 24.0 software (IBM Corp., USA) and the alpha level was set to ≤ 0.05. The results of univariate tests are reported. If the sphericity of variance assumptions were violated the Huynh-Feldt correction procedure was applied and epsilon was reported. Partial eta-squared (η_p^2) was calculated to assess the effect size (ES) of the ANOVAs with small, medium and large ES thresholds defined as > 0.02, > 0.15 and > 0.35, respectively (Cohen, 1992).

Results

FMT

Training Phase

Participants in the NFB group increased their FMT in the training sessions compared to their baseline measures (M = 13%, SD = 23%) and one-sample t-tests confirmed that these increases were statistically significant for most training blocks (Figure 2). The 6 session × 10 block ANOVA revealed no significant effects for session [$F(5, 65) = 0.86$, $p = .59$, $\eta_p^2 = .06$] or block [$F(5.5, 71.6) = 0.73$, $p = .61$, $\eta p^2 = .05$, $\varepsilon = .61$] and no significant session × block interaction effect [$F(45, 585) = 1.00$, $p = .48$, $\eta_p^2 = .07$].

Test Phase

FMT increased from baseline during shooting in the precision shooting test ($M = 36\%$, $SD = 34\%$) and one-sample t-tests confirmed that this increase was statistically significant during the pre- and post-tests for both NFB [$t(13) = 4.52–5.51$, $p \leq .001$] and CON [$t(13) = 2.52–3.53$, $p < .05$]. When separating the standing and prone scores (Figure 3), the 2 group × 2 test ANOVA revealed no main effects for group [standing: $F(1,26) = 2.56$, $p = .12$, $\eta_p^2 = .09$; prone: $F(1,26) = 1.80$, $p = .19$, $\eta_p^2 = .07$] or test [standing: $F(1,26) = 2.05$, $p = .16$, $\eta_p^2 = .07$; prone: $F(1,26) = 2.16$, $p = .15$, $\eta_p^2 = .08$] and no significant group × test interaction effects [standing: $F(1,26) = 0.01$, $p = .92$, $\eta_p^2 = .00$; prone: $F(1,26) = 0.01$, $p = .92$, $\eta_p^2 = .00$].

Shooting Performance and Attentional Focus

Shooting performance and self-reported attentional focus data from the precision shooting test and the simulated performance test, together with interaction effects from the 2 group × 2 test ANOVAs are summarized in Table 2. The group × test interaction effects for shooting accuracy and focus in the simulated performance test approached significance [$F(1,21) = 4.06$, $p = .06$, $\eta_p^2 = .16$ and $F(1,26) = 3.44$, $p = .07$, $\eta_p^2 = .12$, respectively]. There was a significant main effect of test for focus [$F(1,26) = 15.32$, $p < .001$, $\eta_p^2 = .37$], with paired-samples t-tests confirming a significant increase from pre- to post-test for the NFB group [$t(13) = 3.70$, $p < .01$] but not for the CON group [$t(13) = 1.65$, $p = .12$]. There were no other significant main effects of test or group for these variables [all $p \geq .11$, $\eta_p^2 \leq .09$].

Double-Poling Exercise

The results of the 2 group × 2 test × 4 exercise block ANOVAs performed on PO, HR and RPE during the simulated performance tests are presented in the supplementary online material. The analyses indicated that HR was higher in the NFB group compared to the CON group, but there were no pre- to post-test changes in PO, HR or RPE. Importantly, there were no significant differences between the pre- and post-test and there were no significant interaction effects for any of the variables.

Inter-Individual Differences

Eight of the 14 participants (57%) in the NFB group appeared able to consistently increase their FMT and were defined as responders. By contrast, 5 of the 14 NFB participants appeared unable to consistently increase their FMT and were defined as non-responders. One participant did not clearly fall into either category (responder or non-responder) and was therefore omitted from this phase of the analysis.

The mean FMT over each training session and block for the responders (*N* = 8) and non-responders (*N* = 5) are displayed in Figure 4. A 2 group (responder, non-responder) × 6 session × 10 block ANOVA confirmed a significant effect of group [$F(1,11) = 19.26$, $p = <.001$, $\eta_p^2 = .64$], with the responders displaying significantly greater increases in FMT throughout the neurofeedback training intervention compared to the non-responders (change in responders: $M = 23$, $SD = 12\%$; change in non-responders: $M = -2$, $SD = 7\%$). No other significant main effects or interaction effects were identified.

Having established NFB response as a between-participant factor, we performed a series of 2 group (responder, non-responder) × 2 test ANOVAs to explore the potential effects of responsiveness on intervention efficacy. There were no significant group × test interactions for any of the variables (Table 3). However, there were significant main effects of group in the simulated performance test, with responders hitting more targets [$F(1,11) = 11.53$, $p =.006$, $\eta_p^2 = .51$], recording a higher accuracy score [$F(1,7) = 6.90$, $p =.034$, $\eta_p^2 = .50$] and shooting more quickly [$F(1,11) = 7.96$, $p =.017$, $\eta_p^2 = .42$] compared to their non-responder counterparts. There was also a significant main effect for test for self-reported attentional focus, with participants significantly increasing their focus from pre-test to post-test [$F(1,11) = 9.69$, $p =.010$, $\eta_p^2 = .47$].

Discussion

This experiment aimed to assess whether neurofeedback training could increase FMT and improve rifle shooting performance and attentional focus in highly-trained and elite biathletes. Inter-individual variability in responses to the NFB intervention was also explored. We hypothesized a series of interaction effects; the NFB group was expected to increase their FMT, rifle shooting performance and attentional focus from pre- to post-test to a greater extent than the CON group. Additionally, responders to the neurofeedback intervention were expected to improve their shooting performance to a greater degree than non-responders. A borderline significant interaction effect and significant group effect for self-reported attentional focus during the simulated performance test suggests that FMT neurofeedback training promoted a selective increase in attentional focus among members of the NFB group. However, there were no significant group × test interaction effects for FMT or shooting performance. Furthermore, responders failed to show greater improvements in shooting performance from pre- to post-test compared to non-responders. The implications of these findings are discussed below.

Responses during neurofeedback training and pre- to post-test

Analyses of FMT during the training phase of this experiment indicated that participants in the NFB group significantly increased their FMT by an average of 13% from baseline during 3 h (6 sessions × 10 blocks × 3 min) of neurofeedback training. This provides encouraging evidence that skilled biathletes were able to exert some control over their FMT during a relatively brief neurofeedback training intervention. However, this augmentation of FMT that emerged during the dry-firing training phase did not transfer to the live-firing test phase of the experiment, as members of both the NFB and CON groups produced similar FMT, and FMT did not change from the pre- to post-test. It is possible that increased anxiety in the test phase may have masked any training effects, so inducing stress during the training phase and/or measuring anxiety could be worthwhile in future studies. The ecological validity of the intervention could also be increased by delivering neurofeedback training in standing and/or prone positions, to replicate the biathlon environment.

In conjunction with the hypotheses concerning FMT, we also predicted selective improvements in performance from pre- to post-test among members of the NFB group. This was based on the assumption that the NFB group would be able to increase their FMT to a greater extent than the CON group after the neurofeedback intervention, and that this greater ability to increase FMT during aiming would be the mechanism to underpin improved performance (Doppelmayr et al., 2008; Gallicchio et al., 2016; Luchsinger et al., 2016). As our results failed to support the expected group × test interaction for FMT, it is unsurprising that they also failed to support our prediction of beneficial effects of FMT neurofeedback training on shooting performance.

Taken together, our FMT and shooting performance findings contrast with previous meta-analytic results that have shown neurofeedback training to successfully alter cortical activity and improve sports performance (Xiang et al., 2018). For example, neurofeedback has been shown to improve golf putting (Cheng et al., 2015a), dart throwing (Cheng et al., 2015b) and air-pistol shooting performance (Cheng et al., 2017). However, those studies primarily trained SMR power, which is proposed to increase automatic process-related attention in psychomotor tasks (Cheng et al., 2017). As such, it has been suggested that SMR-based neurofeedback training could hold the most promise as a brain-based intervention for improving sports performance (Xiang et al., 2018). We focused on FMT neurofeedback in the present experiment, based on the available data associating FMT with successful rifle shooting performance (Doppelmayr et al., 2008; Gallicchio et al., 2016; Luchsinger et al., 2016). Given that different cortical activity profiles are associated with successful performance across different tasks (Cooke et al., 2018), the neurofeedback interventions employed should target relevant cortical signatures for the task at hand. Therefore, FMT remains a strong candidate for neurofeedback interventions in sports involving shooting, such as biathlon. However, if future studies can demonstrate a relationship between SMR and rifle shooting performance then SMR neurofeedback would certainly be worthy of investigation as an alternative neurofeedback protocol to FMT, especially given the mixed findings of this study and the promising results presented in Xiang et al.'s (2018) meta-analysis.

Future neurofeedback studies could also supplement neurofeedback interventions with instructions designed to help participants learn how to control their brainwaves in the desired way. For example, Chen et al. (2022) demonstrated that supplementing traditional audio and visual FMT neurofeedback with a specific instruction (i.e., focus on your conscious effort) helped participants to modify their FMT to a greater extent than those issued with a vague instruction (i.e., develop your own strategies to control your brainwaves), akin to what we used in the present study. Future research could also use *a priori* EEG monitoring to identify optimal FMT thresholds (i.e., the FMT level that characterizes the most accurate shots) for individual performers (Arns et al., 2008).

Despite failing to support our hypotheses concerning FMT and shooting performance, our results did provide some evidence to suggest that FMT neurofeedback training could potentially enhance attentional focus. Specifically, there was a non-significant trend for a group × test interaction and there was a significant increase in self-reported focus in the simulated biathlon test from pre- to post-test for the NFB group. Improved attention-related mental state has previously been associated with neurofeedback training (Vernon et al., 2003). However, we concede that the effect was small and clearly any improvements in attentional focus in the present study did not translate to improvements in shooting performance. Nevertheless, elevated focus can be linked to heightened perceptions of control and confidence, as well as decreases in stress and anxiety (Jones et al., 2009). Therefore, greater attentional focus may be expected to yield subtle and indirect benefits for performance that are detectable over time or in particularly stressful conditions that were not studied here. This speculation could be further investigated by future research and in the context of the present study, increased focus can be considered as a positive outcome of FMT neurofeedback training.

Inter-individual differences

The second purpose of this experiment was to explore inter-individual differences in response to the neurofeedback training intervention. Our results revealed that 57% and 36% of the participants in the NFB group were respectively considered responders and non-responders, with FMT increasing during training sessions by 23% and 2% in these two sub-groups. Relatively similar incidences of responders (63–75%) and non-responders (25–37%) to neurofeedback training have been reported in previous studies (Enriquez-Geppert et al., 2014; Lubar et al., 1995; Zoefel et al., 2011). Enriquez-Geppert et al. (2014) suggested that the use of ineffective strategies to control the neurofeedback signal could be one reason for non-responders. In the present experiment we encouraged the biathletes to find techniques that would aid them in improving their FMT during the training blocks, but we issued no specific instructions about the thoughts or strategies that would be effective in this context. Some participants verbally indicated that focusing on their front sights and controlling their breathing enabled them to increase their FMT above the threshold for long enough to dry-fire at the target, but clearly not all participants found effective strategies given the prevalence of non-responders. Research has indicated that mediation and breathing techniques to control cardiac autonomic functions have been associated with increased FMT (Kubota et al., 2001; Desai et al., 2015), while reducing conscious effort during motor preparation has been associated with decreased FMT (Chen et al., 2022). Therefore, it may be worth investigating the effectiveness of these different strategies for modifying FMT and rifle shooting performance in future research.

There were no group (responder, non-responder) × test interactions for FMT or shooting performance. However, participants that could more readily increase their FMT during training (i.e., the responders) were characterized by superior shooting accuracy and speed during the simulated performance test compared to the non-responders, as demonstrated by significant group effects. In addition, there was a medium effect ($\eta_p^2 = .25$) for the responders to produce greater FMT compared to the non-responders in the standing condition of the precision test. This provides some evidence to support previous theories that greater FMT is associated with better shooting performance (Dopplemayr et al., 2008; Luchsinger et al., 2016). Our results may also suggest that athletes with superior shooting abilities are able to execute neurofeedback training more effectively. Despite all participants in our experiment being highly-skilled performers, there was clearly inter-individual variability in their shooting scores. This allows us to speculate that the most proficient shooters had a more autonomous shooting process (Fitts & Posner, 1967) and were therefore able to devote more resources to monitoring their FMT (Doppelmayr et al., 2008). Based on this, future applications of neurofeedback training could target the most highly-skilled performers, to help refine their advanced skills, while less skilled shooters could focus on developing their primary skills. This is a novel implication of our study, as much previous neurofeedback research has focused on beginners or improving performers, with the goal of accelerating expertise (e.g., Ring et al., 2015). Focusing on neurofeedback interventions to yield marginal gains in already elite athletes could be a fruitful avenue for future exploration.

Limitations and Future Directions

As suggested earlier in the discussion, increasing the ecological validity of the training phase (e.g., by inducing stress and/or delivering training in standing and prone positions) could be worthwhile. Future research could also consider the use of alternative control groups. The matched regular training control group employed in our study controlled for any improvements attributable to regular (i.e., non-neurofeedback) training, but it did not control for the possibility of effects due to time exposure (i.e., members of the neurofeedback group receiving 3 additional hours of experimenter attention). Given the lack of group × test interaction effects, any benefits that could be attributed to time exposure seem unlikely. However, future studies could include sham feedback or oppositive feedback groups to control for this possibility (Cooke et al., 2018). While multiple control groups in a single study can present a challenge, especially for field-based studies with specialist samples (e.g., highly-trained/elite athletes), a series of studies over time could be valuable. We also acknowledge that the 6 neurofeedback training sessions were not conducted at strictly regular intervals (i.e., they were separated by $M = 2$, $SD = 2$ days) and this was due to the biathletes' demanding schedules. Whether this would affect the efficacy of the intervention is unclear (Gruzelier, 2014), so future research could explore how the timing of neurofeedback training sessions (i.e., the inter-session interval) affects learning and subsequent performance.

Conclusion

Six 30-min neurofeedback training sessions were sufficient to allow most experienced biathletes in the present study to increase FMT while dry-firing their rifle. However, the training intervention was ineffective in elevating FMT or improving rifle shooting performance during live-fire shooting tests, possibly due to participants developing varied, irrelevant or ineffective strategies to shape their FMT. Participants who were most responsive to the neurofeedback intervention, in terms of their FMT increase during dry-firing, tended to be the most proficient shooters during sport-specific shooting tests. This suggests that the most skilled performers may be more receptive to neurofeedback training than less-skilled performers, although this possibility requires further investigation.

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Table 1. *Descriptive characteristics and statistics (M ± SD) for the neurofeedback training (NFB) and control (CON) groups*

	NFB	CON	*P* value
N (women/men)	14 (8/6)	14 (8/6)	-
Left-handed	1	1	-
Age (years)	21.5 ± 1.7	21.9 ± 2.8	0.58
Body mass (kg)	67.0 ± 9.7	70.7 ± 7.4	0.27
Biathlon experience (years)	8 + 4	9 + 3	0.60
Precision shooting score	496 ± 24	498 ± 18	0.83

Note. *P* values are based on independent sample t-tests.

Table 2. *Pre- and post-test shooting and attentional focus scores for the neurofeedback training (NFB) and control (CON) groups*

Measure	**Pre-test**		**Post-test**		**Interaction Effect**
Precision Shooting Test	M	SD	M	SD	
Shooting Score (Prone, out of 109)					
NFB	94.4	4.2	93.3	6.6	*p* = .40
CON	93.6	2.3	94.4	3.4	
Shooting Score (Standing, out of 109)					
NFB	68.0	7.8	71.2	7.7	*p* = .31
CON	70.8	7.0	70.6	6.7	
Focus (Likert scale: 1–10)					
NFB	8	1	8	1	*p* = .47
CON	7	1	8	1	
Simulated Performance Test	M	SD	M	SD	
Targets Hit (out of 20)					
NFB	15	3	16	3	*p* = .78
CON	15	2	16	2	
Shooting Accuracy Score (out of 218)					
NFB	151.9	13.9	147.0	15.1	$p = .06, \eta_p^2 = .16$
CON	142.6	9.4	149.5	11.9	
Total Shooting Time (s)					
NFB	132.7	18.7	131.3	17.8	*p* = .55
CON	128.6	18.3	129.7	18.7	
Focus (Likert scale: 1–10)					
NFB	6	2	8_a	1	$p = .07, \eta_p^2 = .12$
CON	7	2	8	1	

Note. $_a$ indicates significant change from pre-test.

Table 3. *Descriptive statistics (M and SD) and summary of the 2 group (responder, non-responder) × 2 test (pre-test, post-test) ANOVAs*

Measure	**Pre-test**		**Post-test**		**Interaction Effect**
Precision Shooting Test	*M*	*SD*	*M*	*SD*	
Fz Theta Power % increase (Prone)					
Responders	35.29	17.32	49.18	41.23	*p* = .83
Non-Responders	21.52	25.41	30.65	20.60	
Fz Theta Power % increase (Standing)					
Responders	58.44	40.15	64.59	46.58	*p* = .58
Non-Responders	21.02	19.24	41.90	10.68	
Shooting Score (Prone, out of 109)					
Responders	94.7	4.4	95.1	4.9	*p* = .52
Non-Responders	92.7	3.2	90.4	9.2	
Shooting Score (Standing, out of 109)					
Responders	70.0	7.1	72.6	7.7	*p* = .96
Non-Responders	65.3	9.6	68.2	8.5	
Focus (Likert scale: 1–10)					
Responders	8	1	9	1	*p* = .19
Non-Responders	8	1	8	1	
Simulated Performance Test	*M*	*SD*	*M*	*SD*	
Targets Hit (out of 20)					
Responders	16	2	17	2	*p* = .80
Non-Responders	13	4	13	2	
Shooting Accuracy Score (out of 218)					
Responders	155.4	16.5	154.8	12.4	*p* = .33
Non-Responders	144.1	7.9	130.5	6.8	
Shooting Time (s)					
Responders	122.09	12.68	123.89	10.52	*p* = .26
Non-Responders	149.10	17.01	142.87	23.48	
Focus (Likert scale: 1–10)					
Responders	7	2	9_a	1	*p* = .90
Non-Responders	6	1	8_a	1	

Note. $_a$ indicates significant change from pre-test.

Figure 1. *Illustrations of the field-testing setup for (A) an athlete equipped with the EEG electrodes and nylon cap during the standing phase of the precision shooting test (a dummy rifle is pictured here); (B) the target system used for the shooting precision test; (C) an athlete demonstrating double poling on the ski ergometer used for the simulated performance test; (D) the "hit or miss" target system used during the shooting phase of the simulated performance test.*

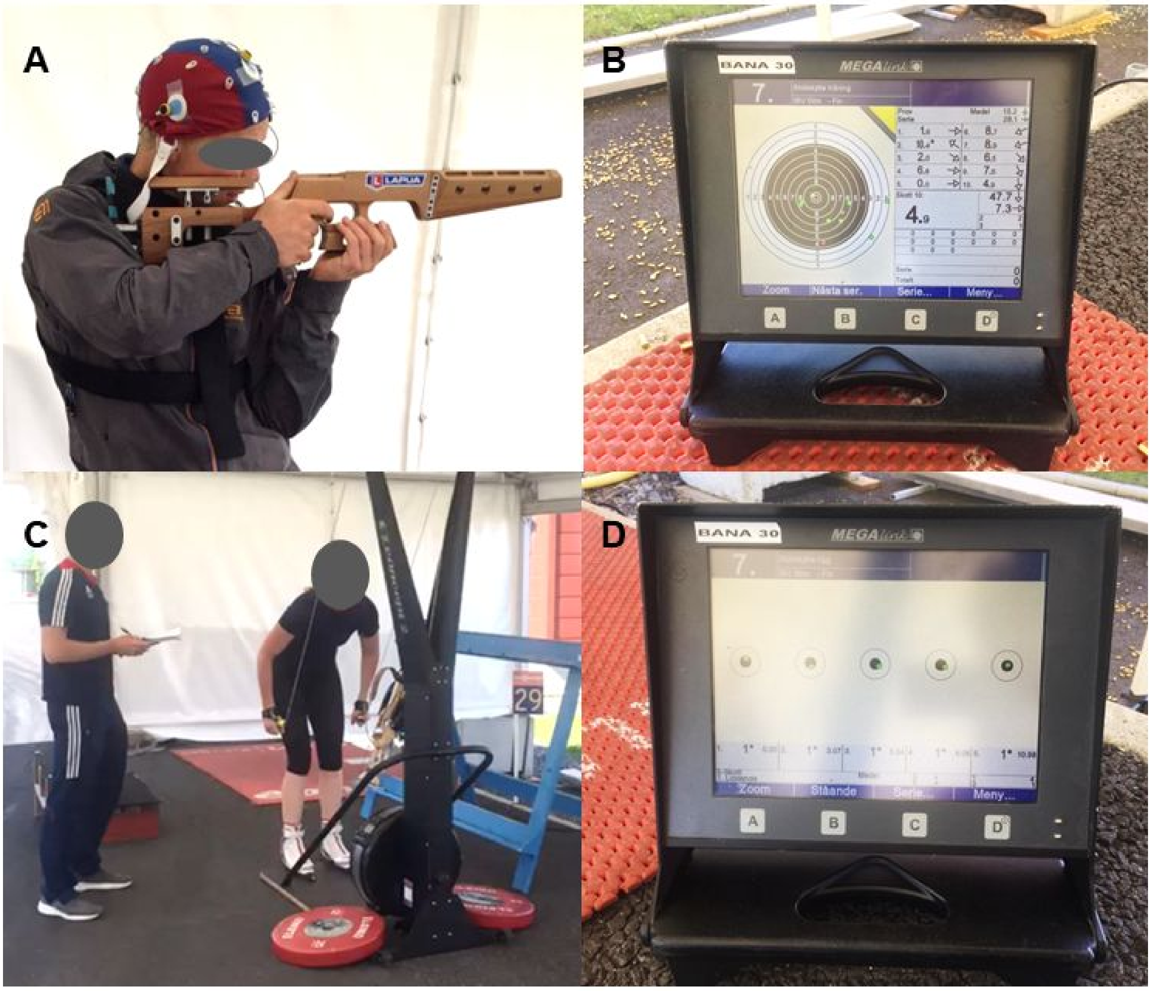
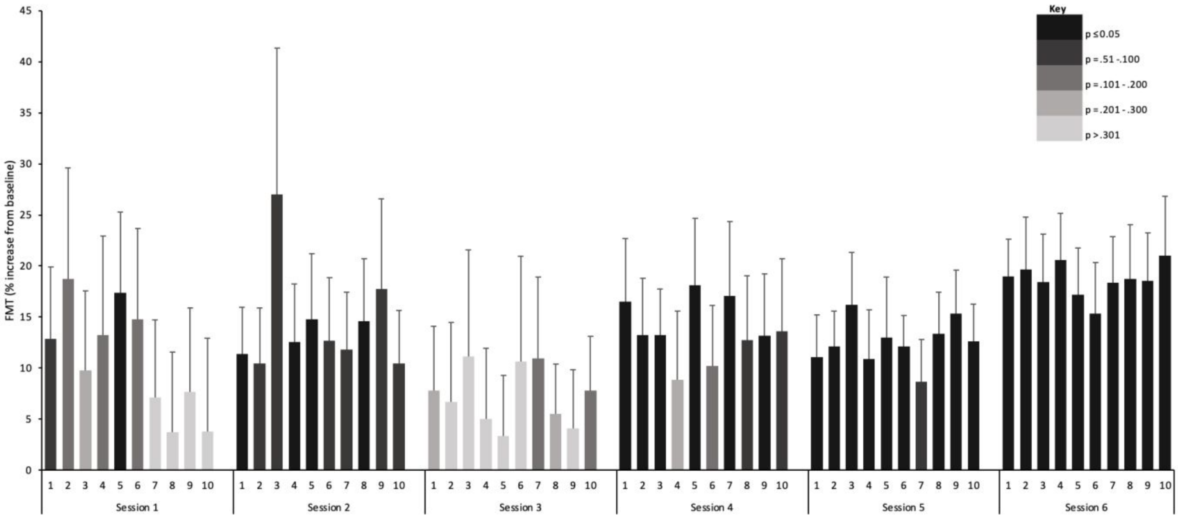
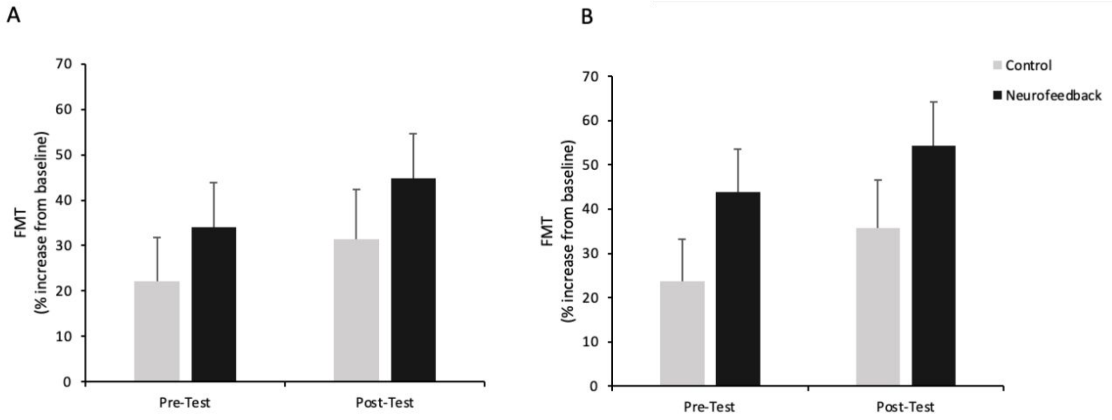


Figure 2. *Relative increase in frontal midline theta power (FMT) from baseline during each 3-min block (1–10) within the six neurofeedback training sessions*



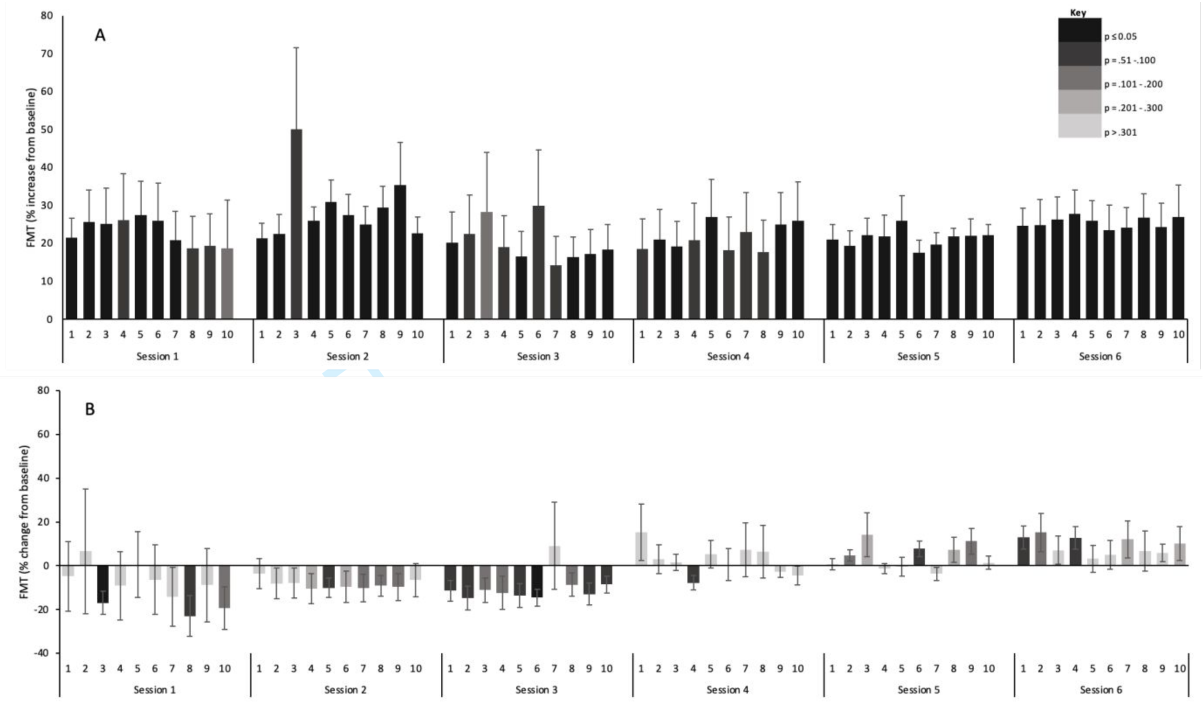
Note. Shading indicates level of significance of the change, with the darkest color signifying blocks where a statistically significant increase in FMT was achieved (P ≤ 0.05). Error bars depict standard error of the means.

Figure 3. *Relative increase in frontal midline theta power (FMT) from baseline during the standing (Panel A) and prone (Panel B) precision shooting tests*



Note. Error bars depict standard error of the means.

Figure 4. *Relative increase in frontal midline theta power (FMT) from baseline during each 3-min block (1–10) within the six neurofeedback training sessions for responders (Panel A) and non-responders (Panel B)*



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NFB	8	1	8	1	*p* = .47
CON	7	1	8	1	
Simulated Performance Test	M	SD	M	SD	
Targets Hit (out of 20)					
NFB	15	3	16	3	*p* = .78
CON	15	2	16	2	
Shooting Accuracy Score (out of 218)					
NFB	151.9	13.9	147.0	15.1	$p = .06, \eta_p^2 = .16$
CON	142.6	9.4	149.5	11.9	
Total Shooting Time (s)					
NFB	132.7	18.7	131.3	17.8	*p* = .55
CON	128.6	18.3	129.7	18.7	
Focus (Likert scale: 1–10)					
NFB	6	2	8_a	1	$p = .07, \eta_p^2 = .12$
CON	7	2	8	1	

Note. $_a$ indicates significant change from pre-test.

Table 3. *Descriptive statistics (M and SD) and summary of the 2 group (responder, non-responder) × 2 test (pre-test, post-test) ANOVAs*

Measure	**Pre-test**		**Post-test**		**Interaction Effect**
Precision Shooting Test	*M*	*SD*	*M*	*SD*	
Fz Theta Power % increase (Prone)					
Responders	35.29	17.32	49.18	41.23	*p* = .83
Non-Responders	21.52	25.41	30.65	20.60	
Fz Theta Power % increase (Standing)					
Responders	58.44	40.15	64.59	46.58	*p* = .58
Non-Responders	21.02	19.24	41.90	10.68	
Shooting Score (Prone, out of 109)					
Responders	94.7	4.4	95.1	4.9	*p* = .52
Non-Responders	92.7	3.2	90.4	9.2	
Shooting Score (Standing, out of 109)					
Responders	70.0	7.1	72.6	7.7	*p* = .96
Non-Responders	65.3	9.6	68.2	8.5	
Focus (Likert scale: 1–10)					
Responders	8	1	9	1	*p* = .19
Non-Responders	8	1	8	1	
Simulated Performance Test	*M*	*SD*	*M*	*SD*	
Targets Hit (out of 20)					
Responders	16	2	17	2	*p* = .80
Non-Responders	13	4	13	2	
Shooting Accuracy Score (out of 218)					
Responders	155.4	16.5	154.8	12.4	*p* = .33
Non-Responders	144.1	7.9	130.5	6.8	
Shooting Time (s)					
Responders	122.09	12.68	123.89	10.52	*p* = .26
Non-Responders	149.10	17.01	142.87	23.48	
Focus (Likert scale: 1–10)					
Responders	7	2	9_a	1	*p* = .90
Non-Responders	6	1	8_a	1	

Note. $_a$ indicates significant change from pre-test.

Figure 1. Illustrations of the field-testing setup for (A) an athlete equipped with the EEG electrodes and nylon cap during the standing phase of the precision shooting test (a dummy rifle is pictured here); (B) the target system used for the shooting precision test; (C) an athlete demonstrating double poling on the ski ergometer used for the simulated performance test; (D) the "hit or miss" target system used during the shooting phase of the simulated performance test.

198x170mm (96 x 96 DPI)

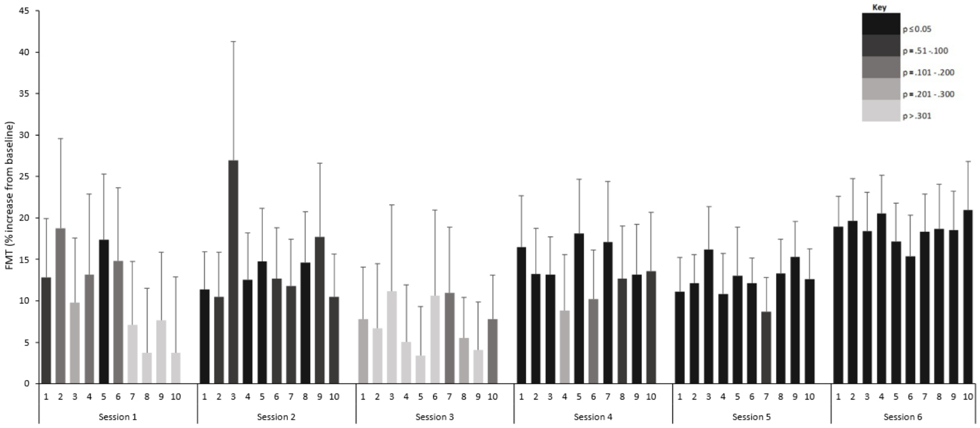

Figure 2. Relative increase in frontal midline theta power (FMT) from baseline during each 3-min block (1–10) within the six neurofeedback training sessions

Note. Shading indicates level of significance of the change, with the darkest color signifying blocks where a statistically significant increase in FMT was achieved (P ≤ 0.05). Error bars depict standard error of the means.

338x190mm (96 x 96 DPI)

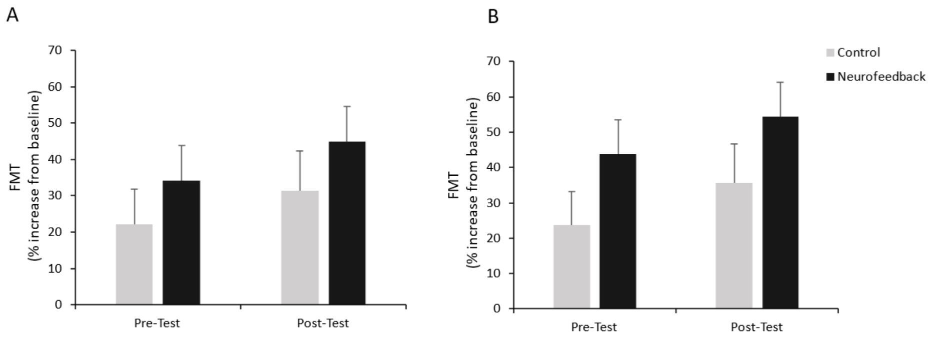

Figure 3. Relative increase in frontal midline theta power (FMT) from baseline during the standing (Panel A) and prone (Panel B) precision shooting tests

Note. Error bars depict standard error of the means.

338x190mm (96 x 96 DPI)

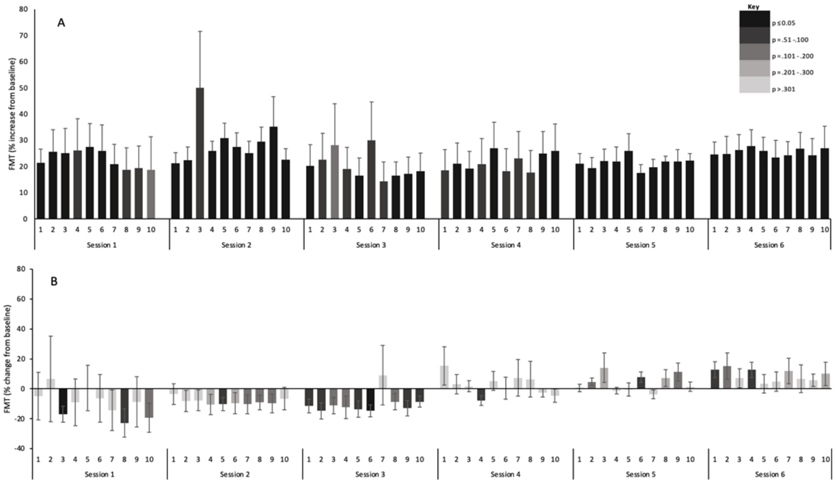

Figure 4. Relative increase in frontal midline theta power (FMT) from baseline during each 3-min block (1–10) within the six neurofeedback training sessions for responders (Panel A) and non-responders (Panel B)

Note. Shading indicates level of significance of the change, with the darkest color signifying blocks where a statistically significant change in FMT was achieved (P ≤ 0.05). Error bars depict standard error of the means.

338x190mm (96 x 96 DPI)

Supplementary Online Material

Descriptive statistics for power output (PO), heart rate (HR) and rating of perceived exertion (RPE) are presented in Table S1. A 2 group x 2 test x 4 exercise block ANOVA revealed a significant main effect of group for HR [$F(1,20) = 9.29$, $p = 0.006$, $\eta_p^2 = .317$], which was higher in the neurofeedback training group (NFB) compared to the control group (CON). There were also main effects of exercise block for HR [$F(3,60) = 102.51$, $p < .01$, $\eta_p^2 = .837$, $\varepsilon = .65$] and RPE [$F(3,78) = 89.00$, $p < .001$, $\eta_p^2 = .77$, $\varepsilon = .55$], with both measures increasing from the first to the last exercise block. No other main or interaction effects reached statistical significance, indicating that participants were able to match their PO, HR and RPE from the pre-test to post-test.

Table S1. Descriptive statistics (*M* and *SD*) for power output (PO), heart rate (HR) and rating of perceived exertion (RPE) recorded during the four exercise blocks (1–4) within the pre/post simulated performance tests for the neurofeedback training group (NFB) and the control group (CON)

Measure	**Pre-Test**								**Post-Test**							
	1		2		3		4		1		2		3		4	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
PO (W)																
NFB	193	62	190	55	185	50	185	51	194	60	191	55	188	52	185	49
CON	187	54	186	54	188	56	187	58	186	54	188	54	187	54	187	55
HR (bpm)																
NFB	163	12	171	10	176	7	176	6	165	9	172	8	177	8	177	8
CON	153	8	163	7	168	8	175	8	151	10	161	10	166	8	168	8
RPE (6-20)																
NFB	15	1	16	1	16	1	16	1	14	1	15	1	16	1	16	1
CON	14	1	16	1	16	1	16	1	14	1	15	1	16	1	16	1