

**Shooting under cardiovascular load: Electroencephalographic activity in preparation for biathlon shooting.**

Galicchio, Germano; Finkenzeller, Thomas; Sattlecker, Gerold; Lindinger, Stefan; Hoedlmoser, Kerstin

**International Journal of Psychophysiology**

DOI:

<https://doi.org/10.1016/j.ijpsycho.2016.09.004>

Published: 01/11/2016

Publisher's PDF, also known as Version of record

[Cyswllt i'r cyhoeddiad / Link to publication](#)

*Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):*

Galicchio, G., Finkenzeller, T., Sattlecker, G., Lindinger, S., & Hoedlmoser, K. (2016). Shooting under cardiovascular load: Electroencephalographic activity in preparation for biathlon shooting. *International Journal of Psychophysiology*, 109, 92-99.  
<https://doi.org/10.1016/j.ijpsycho.2016.09.004>

**Hawliau Cyffredinol / General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

**Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.



## Shooting under cardiovascular load: Electroencephalographic activity in preparation for biathlon shooting



Germano Gallicchio<sup>a,\*</sup>, Thomas Finkenzeller<sup>b</sup>, Gerold Sattlecker<sup>b</sup>, Stefan Lindinger<sup>b</sup>, Kerstin Hoedlmoser<sup>a,\*</sup>

<sup>a</sup> Centre for Cognitive Neuroscience, University of Salzburg, Austria

<sup>b</sup> Department of Sport Science & Kinesiology, University of Salzburg, Austria

### ARTICLE INFO

#### Article history:

Received 19 March 2016

Received in revised form 6 September 2016

Accepted 8 September 2016

Available online 13 September 2016

#### Keywords:

EEG

Frontal-midline theta

Alpha

Cardiovascular exercise

Biathlon shooting

### ABSTRACT

This study explored the influence of sub-maximal cardiovascular load on electroencephalographic (EEG) activity preceding biathlon shooting. Frontal-midline theta and alpha power were examined to assess monitoring processes and cortical inhibition, respectively. Thirteen experienced biathletes (mean age: 17 years; 5 males, 8 females) fired sets of five consecutive shots from the standing position at a 50-meter-distant target, under two fixed-order conditions: (i) at rest and (ii) immediately after 3-minute exercise on a bicycle ergometer at 90% of maximum heart rate (HR). HR and rate of physical exertion (RPE) were measured as manipulation checks. Shooting accuracy was assessed in target rings for each shot. Frontal-midline theta and alpha power were computed in the last second preceding each shot from average-reference 61-channel EEG and inter-individual differences were minimized through a median-scaled log transformation (*Appendix*). HR and RPE increased under cardiovascular load, however, shooting accuracy did not change. Pre-shooting frontal-midline theta power decreased, whereas alpha power increased over temporal and occipital – but not central – regions. These changes were larger for greater HR values. Additionally, higher frontal-midline theta, lower left-central alpha, and higher left-temporal alpha power were associated with more accurate shooting. These findings suggest that monitoring processes are beneficial to shooting performance but can be impaired by sub-maximal cardiovascular load. Greater inhibition of movement-irrelevant regions (temporal, occipital) and concomitant activation of movement-related regions (central) indicate that greater neural efficiency is beneficial to shooting performance and can allow trained biathletes to shoot accurately despite physically demanding conditions.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

### 1. Introduction

Research in precision sports (e.g., gun shooting, archery, golf putting) has provided compelling evidence that electroencephalographic (EEG) activity in preparation for action can distinguish experts from novices and best from worst performance (for review see [Cooke, 2013](#); [Hatfield et al., 2004](#); [Lawton et al., 1998](#)). However, while to date most research has focused primarily on performance at rest, in many sports athletes are often required to perform under conditions of intense cardiovascular load. Accordingly, the present study examined preparation for shooting in biathlon, a winter sport that combines cross-country skiing and rifle shooting.

In a typical biathlon race, two to four sets of five consecutive shots are fired at stationary targets placed at a distance of 50 m from the firing line, either from the standing or the prone position. Each shooting set is preceded and followed by a cross-country skiing lap of 2.5 to 5 km,

during which elite biathletes ski at an average of 85–90% of their maximum heart rate (HR), which represents a sub-maximal intensity ([Hoffman and Street, 1992](#)). A penalty lap or penalty time is given for each target missed and the athlete with the overall fastest time wins the race. In other words, successful performance depends on the trade-off between shooting accurately and shooting and skiing fast. Two studies have examined the effects of different levels of cardiovascular load on shooting performance ([Hoffman et al., 1992](#); [Vickers and Williams, 2007](#)). Both studies confirmed the negative effects of maximal cardiovascular load on the number of target hits – particularly, when shots are fired from the standing position. However, there is no consensus in regards to the effects of sub-maximal load typically observed during biathlon races. On the one hand, [Hoffman et al. \(1992\)](#) found that sub-maximal load (150 bpm) significantly decreased the number of target hits, whereas, on the other hand, [Vickers and Williams \(2007\)](#) found that sub-maximal load (85% of maximum oxygen uptake) did not affect the number of target hits. While these two studies were conducted on a similar population (national teams) and used the same type of physical exercise (bicycle ergometry), it has to be noted that they were published 15 years apart. During this time biathlon scores have improved considerably (<http://biathlonresults.com>), hinting at the fact that

\* Corresponding author at: Centre for Cognitive Neuroscience, University of Salzburg, Hellbrunnerstraße, 34, 5020 Salzburg, Austria.

E-mail addresses: [germano.gallicchio@gmail.com](mailto:germano.gallicchio@gmail.com) (G. Gallicchio), [kerstin.hoedlmoser@sbg.ac.at](mailto:kerstin.hoedlmoser@sbg.ac.at) (K. Hoedlmoser).

modern biathletes, who deliberately train to maximize both shooting accuracy and skiing speed, may adopt compensatory strategies to maintain a proficient shooting accuracy despite the physically demanding conditions. With the aim to shed some light on the neurophysiological adaptations related to these strategies, we examined EEG activity in preparation for biathlon shooting.

Foremost, precision shooting requires that the barrel of the rifle is firmly aligned with the target at the moment of shooting (Ihalainen et al., 2015; Sattlecker et al., 2014). It is plausible to assume that this alignment has to be effectively monitored for the required aiming adjustments to be made. Monitoring processes in the cerebral cortex are primarily associated with the activity of the prefrontal region and can be quantified through examination of frontal-midline theta oscillations (around 4–7 Hz) (for review see Cavanagh and Frank, 2014). A study by Doppelmayer et al. (2008) confirmed the putative link between pre-shooting frontal-midline theta and rifle shooting performance. This study revealed that frontal-midline theta power was higher for expert marksmen than novices in the last second preceding shooting and that it increased consistently within the 3 s preceding shooting for experts, whereas fluctuated inconsistently for novices. Second, but not less important, successful performance requires that irrelevant cognitive processes are inhibited while relevant cognitive processes are enhanced (Hatfield and Hillman, 2001). Cortical oscillations in the alpha frequency (around 8–12 Hz) are attributed an inhibitory function (Klimesch et al., 2007) and, when examined concomitantly in several regions, can reveal the gating of resources away from regions with relative high alpha power towards regions with lower relative alpha power (Jensen and Mazaheri, 2010). Accordingly, cognitive processes related to regions showing high relative alpha power are inhibited, whereas those related to regions showing low relative alpha power are enhanced. Research in precision sport has found that expertise and successful performance is characterized by increased alpha power over temporal and occipital regions (e.g., Hatfield et al., 1984; Kerick et al., 2001; Loze et al., 2001) and decreased alpha power over the central regions (e.g., Babiloni et al., 2008; Cooke et al., 2014; Wolf et al., 2014).

Taken together, these findings suggest that frontal-midline theta power – as a marker of monitoring processes – and regional alpha power – as an indicator of cortical inhibition – are associated with performance and expertise in precision shooting. Intense cardiovascular exercise constitutes a potential perturbation to the relation between pre-shooting cortical activity and shooting performance. Namely, a range of peripheral and central adaptations to the increased cardiovascular load may alter frontal-midline theta power and regional alpha power in preparation for shooting. At the cortical level, the increased demands to sustain the cardiovascular exercise can cause a shift of metabolic resources away from task-irrelevant regions (e.g., prefrontal) and towards regions that are more relevant for movement (e.g., central) during the exercise (Dietrich, 2006). Greater cardiovascular activity (e.g., higher HR) would be followed by stronger shift of resources away from the prefrontal region and, therefore, monitoring processes would be impaired. At the peripheral level, increased metabolic demands call for heightened sympathetic activity and larger release of catecholamines (Obrist, 1981). In order to compensate for the greater arousal consequent to intense cardiovascular exercise, accurate shooting may require greater cortical inhibition, which could alter the balance between activation of shooting-relevant regions and suppression of shooting-irrelevant regions. Pre-shooting frontal-midline theta power and alpha power can be examined to assess the perturbation introduced by cardiovascular load.

In the present study we tested experienced youth biathletes at a shooting task at rest (no-load) and after completing sub-maximal cardiovascular exercise (load). The aims of the study were three-fold. First, to explore experienced biathletes' pre-shooting cortical adaptations to sub-maximal cardiovascular exercise. We expected that cardiovascular exercise would reduce frontal-midline theta power and increase regional alpha power over temporal and occipital regions. Second, to explore the relation between cardiovascular and neurophysiological activity when

shooting under cardiovascular load. We hypothesized that greater HR – as marker of cardiovascular load – would be associated with lower frontal-midline theta power and higher alpha power over temporal and occipital regions. Third, to examine the relation between pre-shooting EEG activity and shooting accuracy. We expected that higher frontal-midline theta power, lower central alpha power and higher temporal and occipital alpha power would be associated with better shooting accuracy.

## 2. Materials and methods

### 2.1. Participants

Thirteen experienced youth biathletes (5 males, 8 females) from the Federal teams of Styria and Salzburg participated in the study. The participants were 17.08 years old ( $SD = 1.66$ ) and reported a training and competition experience of 5 to 8 years. On average, they had a BMI of 20.72 ( $SD = 1.25$ ) and HR-max of 200.39 bpm ( $SD = 6.36$ ). Individual HR-max values were obtained through spiroergometry conducted within the seven months preceding testing. All participants except two were right-handed and all had normal eye sight. Participants were tested at the end of their competition season. Testing took place in an indoor range and required about 2.5 h per participant. The study protocol was approved by the local research ethics committee and all participants gave their informed consent to participate in the study.

### 2.2. Shooting task

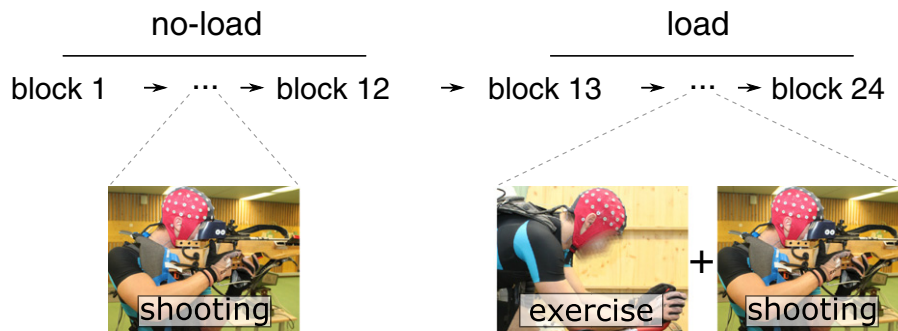
Shots were fired from the standing position at a single, stationary 50 m distant rifle shooting target (diameter of 11.5 cm). Participants were instructed to be as accurate as possible and fire in their individual competition pace (i.e., under time pressure). Sets of five consecutive shots were fired within each of 12 blocks, i.e., 60 shots in total. Participants used their own rifle and all adopted a right-hand shooting stance (i.e., left foot in front, barrel held with the left hand, trigger pulled with the forefinger of the right hand). No feedback was given on the accuracy of each shot. Shots were detected by a microphone interfaced with the system for physiological recording through a stimulus box (StimTracker, Cedrus, CA).

### 2.3. Procedure

Following instrumentation for physiological recording, participants calibrated their rifle and practiced shooting for about 10 min. Then, they completed the shooting task under two fixed-order conditions: first without and then with additional cardiovascular load (Fig. 1). On average, the time interval between consecutive shots was 4.09 s ( $SD = 0.62$ ) and 4.32 s ( $SD = 1.09$ ) for the no-load and the load condition, respectively. Rest recordings (2 min sitting with eyes closed and 2 min sitting with eyes open) were conducted about 10 min before and after the completion of the shooting task.

### 2.4. Cardiovascular load

In the load condition, participants completed a bout of cardiovascular exercise at the beginning of each block, immediately before shooting. Each bout consisted in cycling for 3 min at 90% of the HR-max on an ergometer placed few steps away from the firing line (cf. Hoffman et al., 1992; Vickers and Williams, 2007). HR monitoring (chest belt, Polar Electro, Finland) confirmed that the participants exercised at the required intensity: mean HR of 182.19 bpm ( $SD = 5.22$ ), corresponding to 90.94% ( $SD = 3.14$ ) of HR-max. Before the first exercise bout participants warmed up by cycling at lower intensity (around 60% of HR-max).



**Fig. 1.** The shooting task was completed under two fixed-order conditions. For each no-load block (1–12) participants fired 5 consecutive shots. For each load block (13–24) participants completed a 3-min exercise bout and then fired 5 consecutive shots.

## 2.5. Physiological signals

Sixty-one channels EEG (Fp1, Fpz, Fp2, AF7, AF3, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO5, PO3, POz, PO4, PO6, PO8, O1, Oz, O2), EOG (below the right eye), and bipolar ECG (lead-II montage with electrodes on the right collarbone and the fifth left intercostals space at the midclavicular line) were recorded with ground and reference electrodes placed respectively at CPz and AFz and digitized at 1024 Hz (24-bit resolution) using the eegsport system (ANT Neuro, Netherlands). This system employs active shielding technology that allows the sensor-level signals to be conducted with minimal electrical distortion to an amplifier placed in a backpack. The EEG signals were 1–35 Hz pass-band filtered (FIR filter), re-referenced to the average of all EEG channels and then subjected to Independent Component Analysis (Runica Infomax algorithm, Makeig et al., 1996). The components accounting for blinks, eye movements, and other non-neural activity that could clearly be identified were removed. Time-frequency decomposition was performed through short-time Fast Fourier Transform (FFT) on 17 overlapping segments (overlap of 87.5%), each of the duration of 0.5 s and linearly spaced with centre points ranging from –1000 to 0 ms relative to the execution of the shot (i.e., 0 ms = shot). Prior to FFT, each segment was Hanning-windowed to taper both ends to 0 and then 0-padded to reach 2 s length. This procedure generated FFT coefficients in the time-frequency plane with a precision of 62.5 ms and 0.5 Hz. EEG signals were processed using the EEGLAB toolbox (Delorme and Makeig, 2004) and MATLAB (MathWorks, Natick, MA). The ECG signal was processed using QRSTool (Allen et al., 2007) to detect the occurrences of the R-waves that preceded and followed each shot.

## 2.6. Measures

### 2.6.1. Manipulation checks

Participants rated their physical exertion (RPE) on a 15-point scale (Borg, 1982) ranging from 6 to 20 (6 = *minimal exertion*, 20 = *maximal exertion*). Ratings were performed immediately before shooting in the 1st, 6th, 12th blocks, for the no-load condition, and in the 13th, 18th, and 24th blocks, for the load condition. Values were averaged across blocks to generate a single score for each load condition. HR (bpm) at the moment of shooting was derived from the R-R interval enclosing each shot.

### 2.6.2. Shooting accuracy

The accuracy of each shot was recorded through a computer controlled display (SA 921, SiusAscor, Switzerland) and was measured in target rings ranging from 0 to 10.9 (0 = *outside the outer ring*; 10.9 = *centre of the target*).

### 2.6.3. EEG power

Power spectral density ( $\mu V^2/Hz$ , hereafter “power”) was computed in the time-frequency plane from each FFT coefficient. Power was averaged across time to generate values within 4 epochs: –1000 to –750 ms, –750 to –500 ms, –500 to –250 ms, –250 to 0 ms (0 ms = shot). Following the identification of the Individual Alpha Frequency of each participant (IAF; Klimesch, 1999), power was also averaged over frequencies to generate values in the adjusted theta (IAF–6 to IAF–4) and alpha (IAF–2 to IAF + 2) bands. The IAF was computed twice, one for each of the eyes-closed rest recordings that preceded and followed the shooting task. No difference was revealed between the first IAF ( $M = 9.96$ ,  $SD = 0.99$  Hz) and the second IAF ( $M = 10.12$ ,  $SD = 0.77$  Hz),  $t(12) = 1.67$ ,  $p = 0.12$ , however, these two values were used to adjust the frequency bands in the no-load and load conditions, respectively (cf., Bazanova and Vernon, 2014; Gutmann et al., 2015; Haegens et al., 2014). Frontal-midline theta power was examined at channels Fz, FC1, FCz, FC2, Cz, whereas alpha power was examined in the temporal, occipital, and central regions, in line with our hypotheses: left-temporal (FT7, T7, TP7), left-occipital (PO7, PO5, PO3, O1), left-central (FC3, FC1, C3, C1), right-temporal (FT8, T8, TP8), right-occipital (PO8, PO6, PO4, O2), and right-central (FC4, FC2, C4, C2). Power was averaged across these channels to yield values for each region. No neutral baseline could be identified, therefore non-normal distribution and inter-individual differences were dealt with by employing a median-scaled log transformation (see Appendix). All values were subjected to this transformation; however, for the sake of brevity, we use the term “power” throughout the text.

## 2.7. Statistical analyses

### 2.7.1. Effects of cardiovascular load

Paired-sample *t*-tests (no-load versus load) were conducted on HR and RPE to confirm that our manipulation induced increased load in preparation for shooting. After verifying this requirement, shooting accuracy, and pre-shooting EEG activity (frontal-midline theta and alpha power) were examined. Shooting accuracy was subjected to paired-sample *t*-tests, whereas frontal-midline theta power and alpha power were subjected to repeated-measures ANOVAs with the factors Load (no-load, load), Epoch (–1000 to –750 ms, –750 to –500 ms, –500 to –250 ms, –250 to 0 ms), and, only for alpha, Region (left-temporal, left-occipital, left-central, right-temporal, right-occipital, right-central). The multivariate solution was reported for the ANOVAs when assumption of sphericity was violated (Vasey and Thayer, 1987). Partial eta-squared ( $\eta_p^2$ ) is reported as measures of effect size: values of 0.02, 0.13, and 0.26 were taken to reflect small, medium, and large effects, respectively (Cohen, 1992). Significant effects were interrogated using post hoc Scheffé tests.

### 2.7.2. Effects of HR on EEG power

The influence of HR on either frontal-midline theta power or alpha power, both considered in one epoch ranging from  $-1000$  to  $0$  ms, were examined at the block level. For each of these variables, a time series with 24 time points (i.e., one time point for each shooting block of the aggregated no-load and load conditions) was generated by averaging the respective values across participants. Due to autocorrelation (e.g., HR in block  $n$  is a predictor of HR in block  $n + 1$ ), time-series regressions with autoregressive, moving-average, and exogenous component (ARMAX) were used to control for delayed effects (one lag) of the dependent variable and the associated residuals. HR served as predictor, whereas either frontal-midline theta power or alpha power (in the different regions) served as outcome variable in separate regressions. A dummy predictor accounting for the manipulation of cardiovascular load was not included in the model because of the high collinearity with the HR predictor (Fig. 3B). The contribution of each predictor was assessed through the analyses of the regression coefficients.

### 2.7.3. Effects of EEG on shooting accuracy

The effects of frontal-midline theta power and alpha power on shooting accuracy were examined at the participant level and at the block level. For the participant level, Pearson's correlations were conducted between participants' mean shooting accuracy scores and their mean frontal-midline theta power and alpha power, separately for Load (no-load, load), Epoch ( $-1000$  to  $-750$  ms,  $-750$  to  $-500$  ms,  $-500$  to  $-250$  ms,  $-250$  to  $0$  ms), and, only for alpha, Region (left-temporal, left-occipital, left-central, right-temporal, right-occipital, right-central). In the case that a significant correlation was revealed for one load condition but not the other, the two coefficients were compared using the procedure for repeated-measures designs described by Steiger (1980). This procedure provides a  $z$ -value under the null hypothesis that the two coefficients are equal. For the block level analyses, time-series ARMAX regressions were conducted with shooting accuracy as dependent variable and either frontal-midline theta or alpha power (in the different regions) as predictor variable. The manipulation of cardiovascular load was controlled for by including an appropriate dummy variable as predictor. The unique contribution of each predictor was assessed through the analyses of the regression coefficients.

## 3. Results

### 3.1. Effects of cardiovascular load

**3.1.1. Manipulation checks.** HR,  $t(12) = 20.01$ ,  $p < 0.001$ , and RPE,  $t(12) = 11.60$ ,  $p < 0.001$ , increased from no-load to load (Table 1).

**3.1.2. Shooting accuracy.** Shooting accuracy did not change from the no-load to the load condition (Table 1),  $t(12) = 0.75$ ,  $p = 0.47$ .

**3.1.3. Frontal-midline theta power.** The 2 Load  $\times$  4 Epoch repeated-measures ANOVA revealed a main effect for Load whereby frontal-midline theta power decreased from the no-load to the load condition (Table 1),  $F(1,12) = 13.73$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.534$ . A main effect for Epoch emerged,  $F(3,10) = 21.38$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.865$ . Post hoc testing showed that frontal-midline theta power increased in the last 250 ms whereas it did not change within  $-1000$  to  $-250$  ms. No Load  $\times$  Epoch interaction was revealed,  $F(3,36) = 0.38$ ,  $p = 0.77$ ,  $\eta_p^2 = 0.031$ .

**3.1.4. Alpha power.** The 2 Load  $\times$  4 Epoch  $\times$  6 Region repeated-measures ANOVA revealed a main effect for Load whereby alpha power increased from the no-load to the load condition (Table 1),  $F(1,12) = 19.50$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.618$ . A main effect for Region emerged,  $F(5,8) = 46.56$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.967$ . Scheffé tests showed that alpha power was higher over the temporal and occipital regions than over the central regions (Table 1). No Load  $\times$  Region interaction was found,  $F(5,60) = 1.75$ ,  $p = 0.14$ ,  $\eta_p^2 = 0.127$ , however, Scheffé tests were conducted to examine the *a priori* predicted changes across the different cortical regions. These tests confirmed that alpha power increased from the no-load to the load condition for the temporal and occipital regions however it did not change for the central regions (Table 1). A main effect for Epoch also emerged,  $F(3,10) = 19.81$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.856$ . Scheffé tests revealed that alpha power increased in the last 250 ms whereas it did not change within  $-1000$  to  $-250$  ms. Lastly, the following interactions were revealed: Load  $\times$  Epoch,  $F(3,10) = 5.09$ ,  $p = 0.02$ ,  $\eta_p^2 = 0.604$ , Epoch  $\times$  Region,  $F(15,180) = 2.44$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.169$ , and Load  $\times$  Epoch  $\times$  Region,  $F(15,180) = 1.87$ ,  $p = 0.03$ ,  $\eta_p^2 = 0.135$ . Scheffé tests confirmed that alpha power was overall higher in the load than the no-load condition, however it did not change for the right-central (from  $-1000$  to  $0$  ms), left-central (from  $-250$  to  $0$  ms), and left-temporal (from  $-250$  to  $0$  ms) regions. Additionally, these tests confirmed the temporal trend described above, however, no change across time was revealed for the right-central region in the load condition. Scalp maps for theta and alpha power are showed in Fig. 2.

### 3.2. Effects of HR on EEG power

Time-series regressions were conducted with HR as predictor and either frontal-midline theta power or alpha power (in the different regions) as dependent variables in separate regressions. The coefficients associated with the predictors revealed significant effects of HR on frontal-midline theta power ( $b = -0.01$ ,  $p = 0.01$ ) and on alpha power for all regions ( $bs = 0.01$ – $0.02$ ,  $ps < 0.001$ ) except the right-central ( $b = 0.002$ ,  $p = 0.53$ ). These effects indicated that, independently of lagged effects, the blocks with higher HR were characterized by lower frontal-midline theta power and higher alpha power. The results of all regressions are reported in the Supplementary Material (Table S.2). Fig. 3

**Table 1**

Descriptive statistics of shooting accuracy, HR, alpha power, and frontal-midline theta power as a function of Load (no-load, load), together with the results of statistical testing.

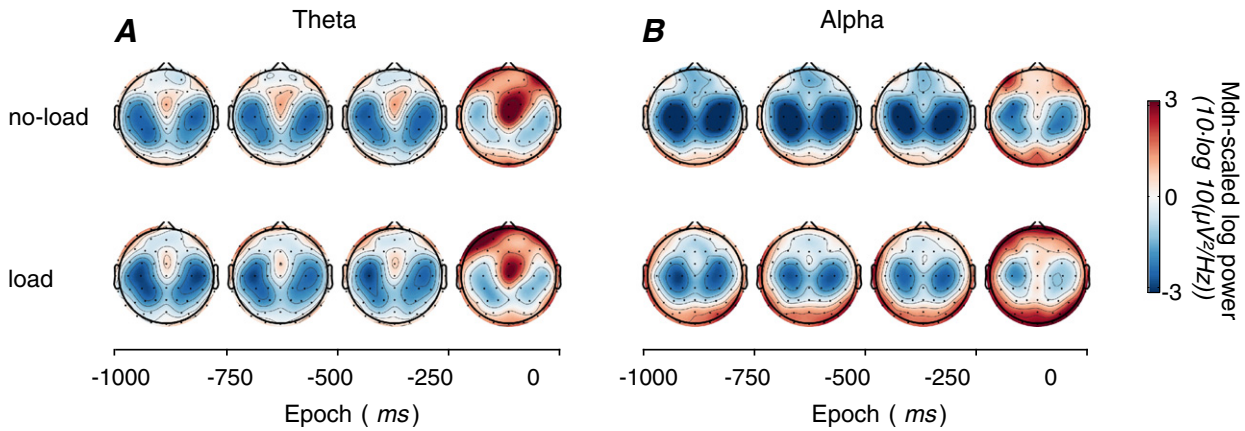
	no-load M (SD)	load M (SD)	$\Delta$ (load – no-load)
Shooting accuracy (0.0–10.9)	4.67 (1.17)	4.50 (1.47)	–0.17
HR (bpm)	73.49 (16.76)	157.21 (19.76)	83.72***
RPE (6–20)	7.18 (1.84)	14.46 (2.34)	7.28***
Frontal-midline theta Mdn-scaled log power ( $10 \cdot \log_{10}(\mu V^2/Hz)$ )	1.00 (0.25)	0.43 (0.15)	–0.57***
Alpha Mdn-scaled log power ( $10 \cdot \log_{10}(\mu V^2/Hz)$ )	–0.04 (0.17)	1.01 (0.18)	1.05***
Left-temporal	1.54 (0.47) <sup>a</sup>	2.77 (0.50) <sup>a</sup>	1.24 <sup>b</sup>
Left-occipital	1.26 (0.26) <sup>a</sup>	2.23 (0.37) <sup>a</sup>	0.97 <sup>b</sup>
Left-central	–2.62 (0.21)	–1.74 (0.14)	0.88
Right-temporal	0.80 (0.31) <sup>a</sup>	1.95 (0.29) <sup>a</sup>	1.15 <sup>b</sup>
Right-occipital	1.17 (0.22) <sup>a</sup>	2.55 (0.36) <sup>a</sup>	1.39 <sup>b</sup>
Right-central	–2.36 (0.30)	–1.69 (0.11)	0.67

\*\* =  $p < 0.01$ .

\*\*\* =  $p < 0.001$ .

<sup>a</sup> = different from left- and right-central (post hoc).

<sup>b</sup> = no-load different from load (post hoc).



**Fig. 2.** Scalp maps representing theta (A) and alpha (B) power averaged across participants, as a function of Load (no-load, load) and Epoch (–1000 to –750 ms, –750 to –500 ms, –500 to –250 ms, –250 to 0 ms).

shows the time series for shooting accuracy, HR, frontal-midline theta power, and regional alpha power.

### 3.3. Effects of EEG on shooting accuracy

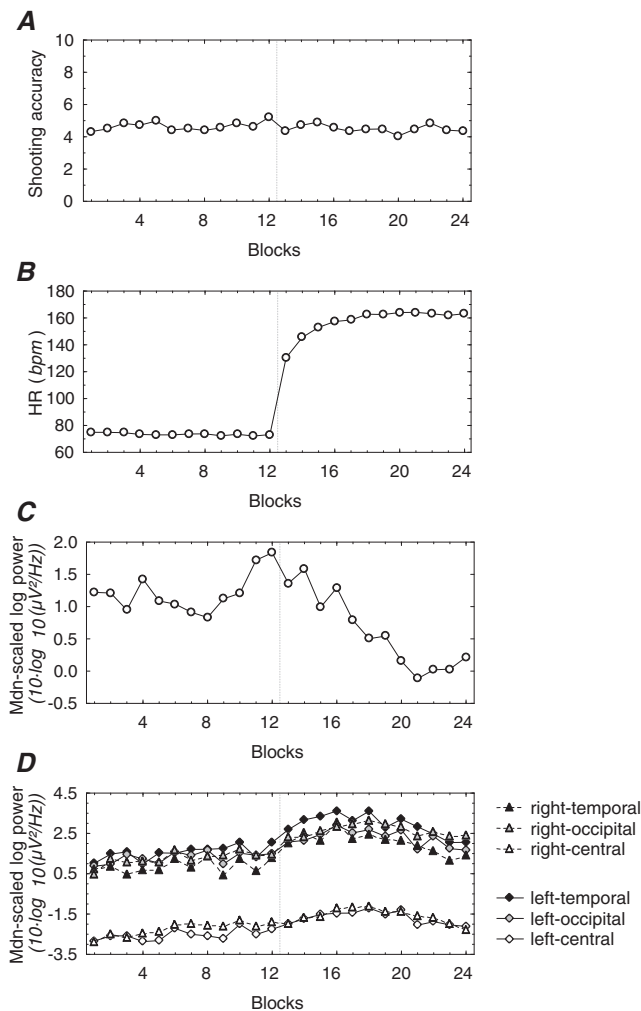
Pearson's correlations were conducted to examine the relation between shooting accuracy and, separately, frontal-midline theta power

and alpha power across participants. In regards to frontal-midline theta power, a positive correlation was found in the 250 ms preceding shooting (Fig. 4A,C). This correlation was significant for the no-load condition,  $r = 0.72$ ,  $p = 0.006$ , but not for the load condition,  $r = 0.38$ ,  $p = 0.21$ , however, these correlations were not significantly different from each other,  $z = 1.70$ ,  $p = 0.09$ . In regards to alpha power, a negative correlation was found in the left-central region between –500 and –250 ms before shooting (Fig. 4B,D). This correlation was significant for the load condition,  $r = -0.62$ ,  $p = 0.03$ , but not for the no-load condition,  $r = 0.17$ ,  $p = 0.57$ . These correlations were significantly different from each other,  $z = 2.04$ ,  $p = 0.04$ . These findings indicate that the participants that showed higher frontal-midline theta power immediately before shooting achieved higher shooting accuracy, particularly under no-load. Under load, participants that showed lower alpha power in the left-central region achieved higher shooting accuracy. The results of all correlations are reported in the Supplementary Material (Table S.1).

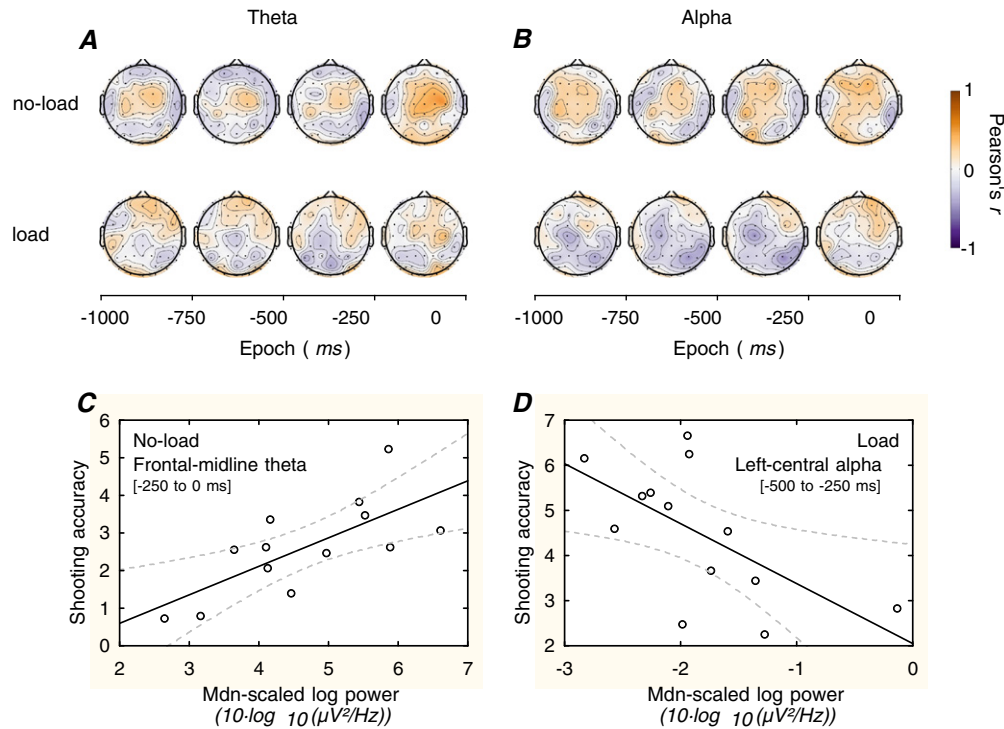
Time-series regressions were conducted at the block level with shooting accuracy as dependent variable. Separate models were run with either frontal-midline theta power or alpha power (one model for each region). A dummy variable was used to control for the effects of the cardiovascular load manipulation. The coefficients associated with the predictors revealed significant effects of left-temporal alpha power ( $b = 0.18$ ,  $p = 0.04$ ) and frontal-midline theta power ( $b = 0.20$ ,  $p < 0.001$ ) on shooting accuracy. These effects indicated that shooting accuracy was higher in the blocks when frontal-midline theta power and left-temporal alpha power were higher. The results of all regressions are reported in the Supplementary Material (Table S.2).

### 3.4. Control analyses

(Fig. 5) Pre-shooting cortical activity was compared to a non-shooting condition. The two eyes-open rest recordings conducted before and after the completion of the shooting task were used as control condition. Frontal-midline theta power and alpha power were averaged across the two rest recordings and compared to the activity related to preparation for shooting (values were considered in a single time interval –1000 to 0 ms and averaged across no-load and load). In regards to frontal-midline theta power, non-shooting and pre-shooting values were compared through a paired-sample  $t$ -test. This analysis revealed that frontal-midline theta power tended to be higher for pre-shooting than non-shooting,  $t(12) = 1.95$ ,  $p = 0.08$ . In regards to alpha power, values were submitted to a 2 Condition (non-shooting, pre-shooting)  $\times$  6 Region (left-temporal, left-occipital, left-central, right-temporal, right-occipital, right-central) repeated-measures ANOVA. Effects for Condition,  $F(1,12) = 4.87$ ,  $p = 0.05$ ,  $\eta_p^2 = 0.289$ , Region,  $F(5,60) = 44.99$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.790$ , and Condition  $\times$  Region,  $F(5,60) = 11.41$ ,



**Fig. 3.** Time series across the aggregated no-load and load blocks for shooting accuracy (A), HR (B), frontal-midline theta power (C), and alpha power (D).



**Fig. 4.** Correlation scalp maps between participants' shooting accuracy and their theta (A) and alpha (B) power, as a function of Load (no-load, load) and Epoch (–1000 to –750 ms, –750 to –500 ms, –500 to –250 ms, –250 to 0 ms). Scatter plots with participants' shooting accuracy as a function of frontal-midline theta power from –250 to 0 ms for the no-load condition (C) and alpha power over the left-central region from –500 to –250 ms for the load condition (D).

$p < 0.001$ ,  $\eta_p^2 = 0.487$ , were revealed. Post hoc Scheffé tests conducted on the interaction effect indicated that alpha topography for pre-shooting was different than that during non-shooting. Namely, in preparation for shooting, the same pattern described in the main analyses was confirmed (i.e., higher power over the temporal and occipital regions compared to the central regions), whereas, for non-shooting, power was higher over the occipital than the central regions, with no difference between the temporal and the other regions examined.

**4. Discussion**

This study examined pre-shooting EEG activity in a group of experienced youth biathletes, at rest (no-load) and immediately following sub-maximal cardiovascular exercise (load). Despite the large increases in HR and RPE, shooting accuracy did not change from no-load to load (cf. *Vickers and Williams, 2007*), suggesting that compensatory strategies were adopted to cope with the increased demands of shooting

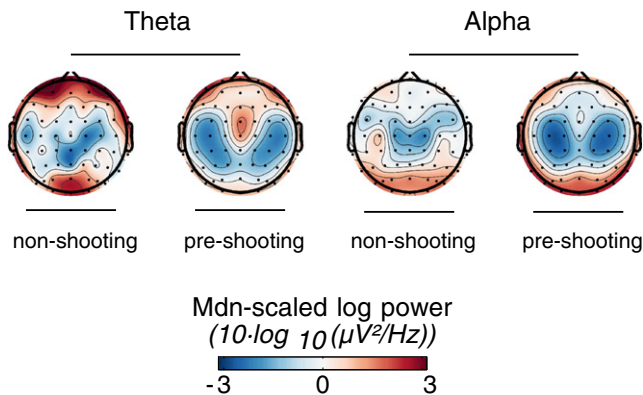
under conditions of intense cardiovascular load. The analyses of frontal-midline theta power and alpha power within the last second preceding shooting revealed effects that can shed some light on these strategies.

**4.1. Preparation for shooting**

Irrespective of cardiovascular load, frontal-midline theta power increased within the last second of preparation with a sharp increase in the last 250 ms (*Fig. 2A*). This effect suggests that resources were allocated to monitoring processes in a timely way (cf. *Doppelmayr et al., 2008*), that is when it is most crucial that the rifle barrel is aligned with the target. Alpha power showed a regional effect compatible with the redistribution of resources away from the temporal and occipital regions (higher alpha power) and towards the central regions (lower alpha power) (*Fig. 2B*) (cf. *Jensen and Mazaheri, 2010*). That these effects are specific to preparation for shooting is supported by control analyses revealing that non-shooting eyes-open rest recordings are characterized by different patterns for both frontal-midline theta power and alpha power (*Fig. 5*).

**4.2. Effects of cardiovascular load**

Pre-shooting frontal-midline theta power was overall reduced under load compared to no-load. Additionally, higher HR values – as a marker of cardiovascular activation – were associated with lower frontal-midline theta power across the shooting blocks. In light of the association between frontal-midline theta power and monitoring processes (*Cavanagh and Frank, 2014*), these findings indicate that fewer resources were deployed to monitoring processes when shots were fired under cardiovascular load, and that greater load was followed by a stronger reduction in monitoring resources. This interpretation is compatible with the account that metabolic resources were shifted away from the prefrontal area following cardiovascular exercise (*Dietrich, 2006*). However, it has to be noted that cardiovascular load did not interfere with the temporal trend whereby frontal-midline theta power increased immediately before shooting.



**Fig. 5.** Scalp maps representing theta and alpha power averaged across participants in non-shooting condition (eyes open rest) and in preparation for shooting.

This suggests that, although in lower amount, monitoring resources were still allocated in a timely way.

Pre-shooting alpha power, oppositely to frontal-midline theta power, increased from the no-load to the load condition. This increase was evident for the temporal and occipital regions but not for the central regions. Additionally, alpha topography was modulated by peripheral activation, whereby higher HR values were associated with increased alpha power in all regions except the right-central. In vein of the inhibitory function attributed to alpha activity across the cortex (Jensen and Mazaheri, 2010; Klimesch et al., 2007), this regional specificity can be interpreted as an adaptation to the increased need to inhibit cognitive activity that is not relevant for shooting, particularly when shots are fired under conditions of greater cardiovascular loads. These findings suggest that cognitive processes operated in the temporal and occipital regions may be not relevant for shooting performance. This result is consistent with previous studies finding that alpha power was higher over temporal and occipital regions than central regions, in preparation for action in precision sports (e.g., Cooke et al., 2014; Kerick et al., 2001).

#### 4.3. Correlates of shooting accuracy

The influence of pre-shooting EEG activity on shooting accuracy was examined from two different perspectives. It is important to note that both perspectives converged towards a single finding. First, we examined the average score of each participant with their average pre-shooting EEG activity. In regards to shooting under rest conditions, we found that the participants who exhibited higher frontal-midline theta power immediately before shooting achieved better accuracy. This effect is consistent with Doppelmayer et al.'s (2008) findings showing that expert marksmen display higher frontal-midline theta power in the last second preceding shooting compared to novices. This effect tended to emerge also when shots were fired under cardiovascular load, however, the association of pre-shooting frontal-midline theta power with shooting accuracy was somewhat lower, perhaps linked to the fact that cardiovascular exercise reduced frontal-midline theta power. Under cardiovascular load, the participants who displayed lower alpha power over the left-central region of the cortex achieved higher shooting accuracy. This effect can be interpreted as less inhibition and more resources being diverted towards the left-central regions, possibly linked to the release of the shot operated by the forefinger of the right hand (cf. Pfurttscheller and Lopes da Silva, 1999). Second, we examined the relation between EEG activity and shooting accuracy across all the different blocks of the aggregated no-load and load conditions. Time-series analyses indicated that participants achieved higher shooting accuracy in the blocks when frontal-midline theta was higher. To the best of our best knowledge, this finding constitutes the first evidence that pre-shooting frontal-midline theta power is associated not just with expertise but also with shooting accuracy within participants. Additionally, higher shooting accuracy was obtained in the blocks where alpha power over the left-temporal region was higher too. This effect is consistent with a number of

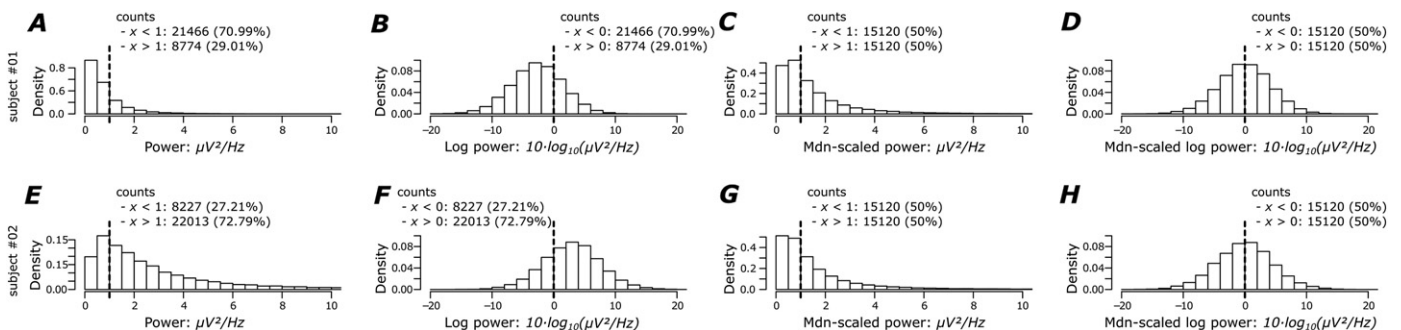
findings indicating that inhibition of left-temporal region of the cortex is beneficial to performance in precision shooting (Hatfield et al., 2004).

#### 4.4. Limitations and future directions

The findings of this study need to be considered in light of a series of limitations. First, cardiovascular load was manipulated in a fixed-order design – i.e., all participants completed the shooting task first at rest and then after cardiovascular exercise. This design choice can introduce a learning effect whereby task performance improved (or did not decrease) because familiarity with the task increased during testing. However, the presence of such confound can be ruled out by observing that if learning had occurred then shooting accuracy would have improved within each load condition, however, this was not the case (Fig. 3A). Nevertheless, we do recommend that future research employs a counter-balanced design to control for possible confounds that vary with what is manipulated. Second, based on the findings of this study we have argued that a series of cortical adaptations can allow experienced biathletes to shoot accurately despite the intense cardiovascular load. This interpretation would have been supported more solidly if our sample included biathletes with larger variability in their skill and expertise level. Namely, it can be predicted that the cortical adaptations that we described are evident for experienced biathletes but less for biathletes with lower experience. We recommend that future studies test this prediction to support or reject our interpretation. Third, our study did not reveal changes in shooting accuracy following sub-maximal cardiovascular exercise, however, it is plausible that different exercise intensities would have affected shooting accuracy differently. It would be useful for future research to investigate the cortical dynamics in preparation for action under different conditions of cardiovascular load (e.g., Hoffman et al., 1992; Vickers and Williams, 2007). Fourth, this study has revealed that pre-shooting EEG activity can affect subsequent shooting accuracy. Earlier studies have revealed that biomechanical factors such as body and rifle sway are also important determinant s of shooting accuracy (Ihalainen et al., 2015; Sattlecker et al., 2014, 2016). It would be interesting for future research to explore the relations between pre-shooting EEG activity and changes to such biomechanical factors. Lastly, we deliberately avoided to interpret selective patterns of neurophysiological activity in terms of cognitive processes because we did not manipulate nor measure cognition directly. While we acknowledge that certain cognitive processes are most likely localized in specific regions of the cortex, the opposite reasoning can generate spurious interpretations (Poldrack, 2006). We suggest future research to manipulate concomitantly physiology and cognition to shed more light on the relation between EEG activity and cognitive processes during preparation for action.

#### 4.5. Conclusions

This study supports the account that experienced biathletes can maintain rest-level shooting accuracy under conditions of sub-maximal



**Fig. A.1.** The EEG power density distributions at the Individual Alpha Frequency (IAF; Klimesch, 1999) in two participants (subject #01: A, B, C, D; subject #02: E, F, G, H) are showed to illustrate the median-scaled log transformation of raw EEG power.



cardiovascular load. Our findings suggest that intense load decreases biathlete's monitoring capacity. However, it is also suggested that these impairing effects can be counter-acted by increased neural efficiency (Hatfield and Hillman, 2001). Namely, resources can be diverted away from shooting-irrelevant cognitive processes (based in the temporal regions of the cortex) and directed towards cognitive processes that are more relevant for shooting (based in the central regions of the cortex). This knowledge advances our understanding of preparation for action in precision sports and can be used to inform training protocols aimed at suppressing irrelevant activity while concomitantly enhancing effective activity.

## Acknowledgments

We would like to thank the biathletes of the Federal teams of Styria and Salzburg for their participation as well as their coach Mark Waldhuber. We are grateful to Wolfgang Klimesch for his highly valuable comments on the manuscript and Daniela Baronner, Kathrin Bothe, Janina Edfelder, Christoph Gressenbauer, Thomas Koller, and Astrid Nußdorfer for their assistance with data collection. Further, we are thankful to ANT Neuro (Enschede, the Netherlands) for kindly providing the recording system employed in this study. This research was supported by the Jacobs Foundation (JS112H).

## Appendix A. Median-scaled log transformation of EEG power

Power distributes according to a  $\chi^2$  function, hence a log transformation is typically used to unskew the distribution and make it conform to a Gaussian (Kiebel et al., 2005). The log transforms numbers smaller and bigger than 1 into negative and positive numbers respectively; however, the proportion of values that are smaller/bigger than 1 varies across individuals (Fig. A.1 A, E). As a consequence, the centre of the Gaussian slides to the left or the right on the basis of such inter-individual differences (Fig. A.1 B, F). With the aim of minimizing such differences a median scaling was performed before log transformation. Raw power values were clustered separately for each participant and frequency bin, so that each cluster included values relative to all other experimental factors – i.e., 2 Load  $\times$  60 Shots  $\times$  4 Epoch  $\times$  63 channels. Values within each cluster were scaled by the median of the cluster, so that the proportion of values smaller/bigger than 1  $\mu V^2/Hz$  was equal to 1 in all clusters (Fig. A.1 C, G). Consequently, the log-transformed power values became symmetric around 0 for all clusters (Fig. A.1 D, H). It is noteworthy that all values within a cluster were scaled by the same scalar therefore within-subjects dynamics are not altered.

## Appendix B. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.ijpsycho.2016.09.004>.

## References

- Allen, J.J.B., Chambers, A.S., Towers, D.N., 2007. The many metrics of cardiac chronotropy: a pragmatic primer and brief comparison of metrics. *Biol. Psychol.* 74 (2), 243–262. <http://dx.doi.org/10.1016/j.biopsycho.2006.08.005>.
- Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., ... Eusebi, F., 2008. Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *J. Physiol.* 586 (1), 131–139. <http://dx.doi.org/10.1113/jphysiol.2007.141630>.
- Bazanov, O.M., Vernon, D., 2014. Interpreting EEG alpha activity. *Neurosci. Biobehav. Rev.* 44, 94–110. <http://dx.doi.org/10.1016/j.neubiorev.2013.05.007>.
- Borg, G.A.V., 1982. Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14 (5), 377–381.
- Cavanagh, J.F., Frank, M.J., 2014. Frontal theta as a mechanism for cognitive control. *Trends Cogn. Sci.* 18 (8), 414–421. <http://dx.doi.org/10.1016/j.tics.2014.04.012>.
- Cohen, J. (1992). A power primer. *Psychol. Bull.*, 112, 155–159. <http://dx.doi.org/10.1037/0033-2909.112.1.155>.
- Cooke, A., 2013. Ready the head and steady the heart: a review of cortical and cardiac studies of preparation for action in sport. *Int. Rev. Sport Exerc. Psychol.* 6, 122–138. <http://dx.doi.org/10.1080/1750984X.2012.724438>.
- Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., McIntyre, D., Ring, C., 2014. Preparation for action: psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology* 51 (4), 374–384. <http://dx.doi.org/10.1111/psyp.12182>.
- Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. <http://dx.doi.org/10.1016/j.jneumeth.2003.10.009>.
- Dietrich, A., 2006. Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Res.* 145 (1), 79–83. <http://dx.doi.org/10.1016/j.psychres.2005.07.033>.
- Doppelmayr, M., Finkenzeller, T., Sauseng, P., 2008. Frontal midline theta in the pre-shot phase of rifle shooting: differences between experts and novices. *Neuropsychologia* 46, 1463–1467. <http://dx.doi.org/10.1016/j.neuropsychologia.2007.12.026>.
- Gutmann, B., Mierau, A., Hülzdünker, T., Hildebrand, C., Przyklenk, A., Hollmann, W., Strüder, H.K., 2015. Effects of physical exercise on individual resting state EEG alpha peak frequency. *Neural Plasticity* 2015, 1–6. <http://dx.doi.org/10.1155/2015/717312>.
- Haegens, S., Cousijn, H., Wallis, G., Harrison, P.J., Nobre, A.C., 2014. Inter- and intra-individual variability in alpha peak frequency. *NeuroRegionmage* 92, 46–55. <http://dx.doi.org/10.1016/j.neuRegionmage.2014.01.049>.
- Hatfield, B.D., Hillman, C.H., 2001. The psychophysiology of sport: A mechanistic understanding of the psychology of superior performance. In: Singer, R.N., Hausenblas, H.A., Janelle, C.M. (Eds.), *Handbook of sport psychology*, 2nd Wiley, pp. 362–386.
- Hatfield, B.D., Landers, D.M., Ray, W.J., 1984. Cognitive processes during self-paced motor performance: an electroencephalographic profile of skilled marksmen. *Journal of Sport Psychology* 6 (1), 42–59.
- Hatfield, B.D., Haufler, A.J., Hung, T.M., Spalding, T.W., 2004. Electroencephalographic studies of skilled psychomotor performance. *J. Clin. Neurophysiol.* 21, 144–156. <http://dx.doi.org/10.1097/00004691-200405000-00003>.
- Hoffman, M.D., Street, G.M., 1992. Characterization of the heart rate response during biathlon. *Int. J. Sports Med.* 13 (5), 390–394.
- Hoffman, M.D., Gilson, P.M., Westenburg, T.M., Spencer, W.A., 1992. Biathlon shooting performance after exercise of different intensities. *Int. J. Sports Med.* 13 (3), 270–273.
- Ihalainen, S., Kuitunen, S., Mononen, K., & Linnamo, V. (2015). Determinants of elite-level air rifle shooting performance. *Scandinavian Journal of Medicine & Science in Sports*. <http://dx.doi.org/10.1111/sms.12440>.
- Jensen, O., Mazaheri, A., 2010. Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Front. Hum. Neurosci.* 4, 1–8. <http://dx.doi.org/10.3389/fnhum.2010.00186>.
- Kerick, S.E., McDowell, K., Hung, T.M., Santa Maria, D.L., Spalding, T.W., Hatfield, B.D., 2001. The role of the left temporal region under the cognitive motor demands of shooting in skilled marksmen. *Biol. Psychol.* 58 (3), 263–277. [http://dx.doi.org/10.1016/S0301-0511\(01\)00116-8](http://dx.doi.org/10.1016/S0301-0511(01)00116-8).
- Kiebel, S.J., Tallon-Baudry, C., Friston, K.J., 2005. Parametric analysis of oscillatory activity as measured with EEG/MEG. *Hum. Brain Mapp.* 26 (3), 170–177. <http://dx.doi.org/10.1002/hbm.20153>.
- Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Rev.* 29, 169–195. [http://dx.doi.org/10.1016/S0165-0173\(98\)00056-3](http://dx.doi.org/10.1016/S0165-0173(98)00056-3).
- Klimesch, W., Sauseng, P., Hanslmayr, S., 2007. EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Res. Rev.* 53, 63–88. <http://dx.doi.org/10.1016/j.brainresrev.2006.06.003>.
- Lawton, G.W., Hung, T.M., Saarela, P., Hatfield, B.D., 1998. Electroencephalography and mental states associated with elite performance. *Journal of Sport & Exercise Psychology* 20, 35–53.
- Loze, G.M., Collins, D., Holmes, P.S., 2001. Pre-shot EEG alpha-power reactivity during expert air-pistol shooting: a comparison of best and worst shots. *J. Sports Sci.* 19 (9), 727–733. <http://dx.doi.org/10.1080/02640410152475856>.
- Makeig, S., Bell, A.J., Jung, T.P., Sejnowski, T.J., 1996. Independent component analysis of electroencephalographic data. In: Touretzky, D., Mozer, M., Hasselmo, M. (Eds.), *Advances in Neural Information Processing Systems* Vol. 8. MIT Press, Cambridge, MA, pp. 145–151.
- Obrist, P.A., 1981. *Cardiovascular Psychophysiology*. Plenum Press, New York, NY.
- Pfurtscheller, G., Lopes da Silva, F.H., 1999. Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clin. Neurophysiol.* 110 (11), 1842–1857. [http://dx.doi.org/10.1016/S1388-2457\(99\)00141-8](http://dx.doi.org/10.1016/S1388-2457(99)00141-8).
- Poldrack, R.A., 2006. Can cognitive processes be inferred from neuroimaging data? *Trends Cogn. Sci.* 10 (2), 59–63. <http://dx.doi.org/10.1016/j.tics.2005.12.004>.
- Sattler, G., Buchecker, M., Müller, E., Lindinger, S.J., 2014. Postural balance and rifle stability during standing shooting on an indoor gun range without physical stress in different groups of biathletes. *Int. J. Sports Sci. Coach.* 9 (1), 171–183. <http://dx.doi.org/10.1260/1747-9541.9.1.171>.
- Sattler, G., Buchecker, M., Gressenbauer, C., Müller, E., Lindinger, S.J., 2016. Factors discriminating high from low score performance in biathlon shooting. *International Journal of Sports Physiology and Performance* <http://dx.doi.org/10.1123/ijsp.2016.0195>.
- Steiger, J. H. (1980). Tests for comparing elements of a correlation matrix. *Psychol. Bull.*, 87, 245–251. <http://dx.doi.org/10.1037/0033-2909.87.2.245>.
- Vasey, M.W., Thayer, J.F., 1987. The continuing problem of false positives in repeated measures ANOVA in psychophysiology: a multivariate solution. *Psychophysiology* 24, 479–486. <http://dx.doi.org/10.1111/j.1469-8986.1987.tb00324.x>.
- Vickers, J. N., & Williams, A. M. (2007). Performing under pressure: the effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *J. Mot. Behav.*, 39(5), 381–394. <http://dx.doi.org/10.3200/JMBR.39.5.381-394>.
- Wolf, S., Brölz, E., Scholz, D., Ramos-Murguialday, A., Keune, P.M., Hautzinger, M., ... Strehl, U., 2014. Winning the game: brain processes in expert, young elite and amateur table tennis players. *Front. Behav. Neurosci.* 8. <http://dx.doi.org/10.3389/fnbeh.2014.00370>.