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Darts fast-learning reduces theta power but is not affected by Hf-tRNS: A behavioral and electrophysiological investigation

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ABSTRACT

Sports trainers have recently shown increasing interest in innovative methods, including transcranial electric stimulation, to enhance motor performance and boost the acquisition of new skills during training. However, studies on the effectiveness of these tools on fast visuomotor learning and brain activity are still limited. In this randomized single-blind, sham-controlled, between-subjects study, we investigated whether a single training session, either coupled or not with 2 mA online high-frequency transcranial random noise stimulation (hf-tRNS) over the bilateral primary motor cortex (M1), would affect dart-throwing performance (i.e., radial error, arm range of motion, and movement variability) in 37 healthy volunteers. In addition, potential neurophysiological correlates were monitored before and after the training through a 32-electrode portable electroencephalogram (EEG). Results revealed that a single training session improved radial error and arm range of motion during the dart-throwing task, but not movement variability. Furthermore, after the training, resting state-EEG data showed a decrease in theta power. Radial error, arm movement, and EEG were not further modulated by hf-tRNS. This indicates that a single training session, regardless of hf-tRNS administration, improves dart-throwing precision and movement accuracy. However, it does not improve movement variability, which might require multiple training sessions (expertise resulting in slow learning). Theta power decrease could describe a more efficient use of cognitive resources (i.e., attention and visuomotor skills) due to the fast dart-throwing learning. Further research could explore different sports by applying longer stimulation protocols and evaluating other EEG variables to enhance our understanding of the lasting impacts of multi-session hf-tRNS on the sensorimotor cortex within the framework of slow learning and training assistance.

1. Introduction

The sport of darts is a discipline of international competition, combining precision, technique, and strategy, proving to be a product of the intricate synergy between muscular and central nervous systems. Although dart-throwing is a discrete movement, it involves a sequence of psychomotor phases, including aiming, swinging, accelerating, releasing the dart, and completing the throw by receiving feedback on the result (Tumialis et al., 2020). Thus, a player's ability in dart-

throwing depends not only on physical dexterity but also on the neural processes that regulate movement, aim, and timing of the throw. With each throw, the athlete must draw from past motor learning experiences of the throwing skill and proprioceptive feedback. Beyond the apparent simplicity of the sport lies an unexplored field where scientific knowledge meets precision sports performance. The quality of a dart throw is determined objectively by the distance between the point at which the dart perforates the board and the intended target location. This distance is called *radial error*. The reduction of radial error, and thus

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better throws, can be obtained by increasing movement consistency through a reduction of both the timing of the release and hand and arm trajectory variability (Nasu et al., 2014). Optimal performance over the regulation distance (2.37 m) is achieved through a combination of arm speed and dart release angle which is then consistently reproduced throughout a match. Such visuomotor adaptations occur in under 1 ms at the point of release with significant negative consequences for performance with seemingly minor perturbations (Calvin, 1983; Chowdhary and Challis, 1999; Loosh et al., 1999).

Practice and repetition of a motor task allow neuromotor adaptations, which lead to improved performance and skill acquisition; this process can be defined as motor skill learning. In the context of throwing tasks, the improvement in sensorimotor skills consists of a change in the speed-accuracy relationship. Indeed, moving with accuracy is a central goal of motor skills learning. An indicator of motor skill learning is a more accurate throw obtained through the optimization of throwing movement (i.e., reduction of error; Jackson et al., 2019; Lefebvre et al., 2012; Shmuelof et al., 2012). Moreover, higher movement consistency (i.e., lower movement variability) between throws contributes to defining a high skill level of performance (Guthrie, 1935; Wulf, 2013). These changes are indicative of improved feedback control and suggest that motor and sensory cortical representations play a pivotal role in reducing such variability (Shmuelof et al., 2012).

1.1. Neuropsychological correlates of motor skill learning

Practice and repetition of a task or skill appear to promote neuromotor adaptations that are characterized by improved performance and skill acquisition. These are core elements of motor skill learning, which is defined as an improved ability in sensorimotor coordination (Meek et al., 2021). The motor cortex, including both the primary (M1) and secondary motor cortices, is responsible for encoding motor sequences and facilitating the transition to performing movements. This is achieved through coordinated neuronal activity that reflects motor maps shaped by motor learning processes (Fritsch et al., 2010). Fast learning (or online learning), induced by single training, can transiently enhance throwing accuracy, including a reduction in radial error and movement variability (Jacobson et al., 2022; Karni et al., 1998; Meek et al., 2021). On the other hand, slow learning, resulting from prolonged multi-session training, leads to the consolidation of these improvements ultimately resulting in higher throwing performance consistency (Bao et al., 2016).

Episodes of fast learning might occur in single games of pool, sporadic dart-throwing sessions, or attempts to dunk with a basketball (Meek et al., 2021): in these cases, the learner engages in isolated tasks without the intention of continuing with regular, planned, and intensive practice, but with the sole aim of winning a single game. During fast learning, there is an increase in activation in regions of the brain such as the premotor cortex (PMC), the supplementary motor area (SMA), the parietal cortex, the striatum, and the cerebellum, structures implicated in the learning processes of motor parameters and associated with increased activation as learning progresses (Costa et al., 2004). The M1 plays a fundamental role in the acquisition of motor skills because the outputs descending from M1 through the spine to the muscles derived from the synchronized activity of somatotopically organized neurons, arranged to create motor maps (Kami et al., 1995). The interactions between the M1, PMC, and SMA and their involvement in managing motor sequences are crucial for the fast learning of motor skills (Hikosaka et al., 2002). These results are also confirmed by studies on mice, where prevalent recruitment of M1 neurons during the initial phases of motor skill training was associated with the modulation of synaptic efficacy through long-term potentiation (LTP) and long-term depression (LTD) (Costa et al., 2004).

The neurophysiological correlates of motor learning can be assessed in humans with Electroencephalography (EEG). Specifically, through the analysis of the power spectral density (PSD), it is possible to assess

changes in neural oscillations, the rhythmic patterns of electrical activity resulting from the synchronized firing of neurons ensembles (Uhlhaas & Singer, 2012). These rhythmic patterns can be observed in various frequency bands, typically classified in Delta (δ , 1–4 Hz) and Theta (θ , 4–8 Hz), Alpha (α , 8–13 Hz), Beta (β , 13–30 Hz) and Gamma (γ , 30–100 Hz). For instance, an increase in α power over the M1 cortical brain area has been reported due to visuomotor training (Gentili et al., 2015; McAllister et al., 2011). In addition, improvements in visuomotor performance after training have been associated with enhanced β and θ power (Espenhahn et al., 2019; Krause et al., 2016; Rozengurt et al., 2016). Controversially, other studies reported an increase in low-frequency bands (θ and δ) in front-central channels immediately after motor training (Aliakbaryhosseiniabadi et al., 2021). The learning process of dart-throwing can induce changes in the β band, associated with increased activity in frontal and parieto-occipital regions and decreased activity in central regions; a difference in EEG activity patterns between individuals performing the throwing task with the dominant hand and those using the non-dominant hand is also observed (Khanjari et al., 2023). In summary, these findings suggest that motor learning impacts EEG patterns and that distinct motor control programs may exist for the dominant and non-dominant hands. A recent review of EEG analysis methods and their relation to the impact of exercise on EEG signals revealed some inconsistencies, mainly methodological issues such as small sample sizes and varying techniques, hindering the generalizability and replicability of findings and leading to constrained conclusions (Gramkow et al., 2020). However, the review is exclusively focused on endurance and strength sports; therefore, deepening the electrophysiological changes in precision sports, i.e. dart-throwing and air-shooting, is necessary.

1.2. Non-invasive brain stimulation (NIBS) techniques and motor skill learning

There has been growing interest in using Non-invasive Brain Stimulation (NIBS) techniques to modulate motor skill learning. While the application of NIBS in sports raises concerns about neurodoping, it differs from traditional doping, which involves drugs to enhance physical performance. Neurodoping aims to improve both athletic and cognitive skills, and though the field is still evolving, it poses ethical questions (Davis, 2013). Unlike performance-enhancing drugs that boost strength and endurance, NIBS effects depend on rigorous training. Thus, NIBS could be considered a supportive tool if used in conjunction with extensive athletic preparation, thereby maintaining the spirit of fair competition. Specifically, transcranial electrical stimulation (tES), by modulating brain excitability, could support athletes during training and enhance their performance (Meek et al., 2021).

tES consists of the administration of weak painless currents via electrodes placed over the scalp (Polanía et al., 2018). During stimulation, current flows through the skull and reaches the cortex altering the neuron's membrane potential and their excitability (Miranda et al., 2018). As suggested in a meta-analysis by Maudrich et al. (2022) transcranial direct current stimulation (tDCS) over M1 and other motor regions (Buch et al., 2017) exerts positive effects on fast learning. To date, tDCS has proved its potential in the enhancement of athletes' performance in simple motor tasks as well as sports performances such as endurance (e.g., cycling; Okano et al., 2015), power (e.g., long and high jump; Lattari et al., 2020), and dribbling or spiking skills (e.g. in basketball and volleyball; Moscaleski et al., 2022; Park et al., 2023). For instance, 20-minute of anodal tDCS over M1 during dart-throwing training can improve the skill's acquisition and meaningfully contribute to a positive training effect (Meek et al., 2021).

In addition to tDCS, transcranial random noise stimulation (tRNS) can modulate brain excitability via the application of a weak white noise-like stimulation ranging from 0 to 100 Hz (low-frequency) or 100–600 Hz (high-frequency; hf-tRNS) (Brancucci et al., 2023). The application of hf-tRNS over M1 has a facilitatory effect on motor-evoked

potentials (MEPs; Moret et al., 2019; Terney et al., 2008), albeit the effects of tRNS in sports and training contexts remain largely unexplored (Brancucci et al., 2023). Through stochastic facilitation, tRNS modulates neural cortex oscillations, reducing the neuronal activation threshold (McDonnell and Ward, 2011). Due to resonance processes, a randomized activity (a noise) is induced at the cortical level, enhancing the sensitivity of neurons which spike even after weaker inputs (Moss et al., 2004; Ward, 2009). Another explanation of the physiology of tRNS is to be sought in the repetitive opening of sodium channels due to the stimulation, leading to a reduced hyperpolarization of the neuron (Chaieb et al., 2009; Terney et al., 2008). Another peculiarity of tRNS is the absence of polarity constraints and perceptible and potentially uncomfortable skin sensations when applied (Chaieb et al., 2009). Albeit Fertonani et al. (2011) showed that hf-tRNS induces a performance improvement in perceptual learning higher than lf-tRNS and tDCS, to date only a few studies have investigated its effect on visuomotor skill learning in sports. Particularly, while de Albuquerque et al. (2019) tested the hf-tRNS effect on motor skill learning, finding no significant effect on golf practice, Tommasi et al. (2015) showed that hf-tRNS improved the shooting performance of a skilled air-pistol shooter.

1.3. Aims and hypotheses

Given the small and inconsistent literature on the topic, the current study aims to investigate the effect of a single session of dart-throwing training on darts performance in non-professionals. Dart-throwing was chosen for its simplicity, reproducibility, and easily measurable outcomes and movements, which make it an ideal model for studying motor skill learning. Thus, while previous research has focused on wrist movement and throwing timing, little attention has been given to the effect of a single training session on arm movement during dart-throwing. Further, we aim to understand whether the application of hf-tRNS can influence fast learning outcomes. To our knowledge, this is the first study investigating the combined impact of motor skill training and M1 hf-tRNS on darts performance. Secondly, we explored the impact of dart training (and thus of fast learning) and hf-tRNS on resting state EEG (rs-EEG) power spectrum density. This multimodal approach allows a deeper understanding of the mechanisms involved in motor skill training.

Particularly, we postulate that a single session of dart-throwing training should induce fast motor learning and improve throwing performance in terms of decreased radial error and movement variability, and increased arm range of motion (H1a). Furthermore, we explore the potential modulating effects of hf-tRNS on dart-throwing outcomes. Specifically, we hypothesize that hf-tRNS may influence throwing performance (H1b). Moreover, we explore the effects of dart-throwing training coupled or not with hf-tRNS on rs-EEG PSD for each frequency band, to test whether the training and the tRNS can modulate resting-state brain oscillations.

2. Materials and method

2.1. Participants

Using GPower 3.1 (University of Kiel, GER), we conducted a power analysis based on two studies with similar designs (Manippa et al., 2017; Meek et al., 2021) to determine the required sample size for testing our hypotheses. With the alpha level set at 0.05 and power at 0.95, the calculations indicated that a mixed within-between ANOVA (2*2*2) would require a sample size ranging from 28 (Meek et al., 2021) to 40 (Manippa et al., 2017) participants. Based on this result, thirty-seven adults (6 female) were recruited. Their age ranged between 18 and 52 years old ($M=25.2$; $SD=7.7$). Two of them were ambidextrous, 3 were left-handed and the rest were right-handed. They were asked to report their darts expertise in the last 6 months: 28 participants declared to have never played darts in the last 6 months, 7 of them played darts

once or once a month and only 2 participants declared to have played darts more than once a month or every week during the last 6 months. All participants were healthy with normal or corrected-to-normal vision and had no self-reported injuries to the upper limbs that would have limited their ability to perform a throwing motion. All of them fulfilled the inclusion criteria for transcranial electric stimulation (Nitsche et al., 2003). As participants were screened into the study, they were blindly assigned to two different tRNS group conditions (sham or *verum* hf-tRNS) matching the groups on age, sex, handedness, and darts expertise (see Table 1).

2.2. Experimental protocol

The following procedures were approved by the Ethics and Integrity SubCommittee (EISC) of the University of East London (UEL) and conducted according to the Declaration of Helsinki. The study was a single-blind, randomized between-subjects, sham-controlled design. The experimental protocol was carried out in a quiet and illuminated room by using metal darts. Participants were positioned behind a yellow line at 237 cm from a black and white dart target (42.5 cm diameter) which was placed on the wall at 173 cm height from the floor to the center of the dart target. To video-record the protocol, a GoPro Hero 8 was positioned contralateral to the arm used in the dart-throwing to get an inside view of the movement. Participants were instructed to hit the target's bullseye (i.e., the center of the target) as accurately as they could. Particularly, the experimental protocol, which lasted about 60 min, was divided into 3 sessions: (i) the *pre-training session* consists of resting state EEG (eyes open for 5 min) recording, followed by a dart-throwing familiarization task (three throws per hand) and the dart-throwing task consisting of 20 consecutive trials (i.e., throws) per hand; (ii) the *training session* consists of 3 min of free throwing (max 36 throws) per hand; (iii) the *post-training session* consists of the repetition of the dart-throwing task (20 consecutive throws per hand) followed by the rs-EEG recording (5 min eyes opened). Between the pre-training dart-throwing task and the training session, there was a 5-minute break when the tRNS (either sham or hf-tRNS) was activated. Subsequently, tRNS was administered *online* during the training session and the post-training dart-throwing task (Fig. 1).

During the familiarization and training session, the target was left uncovered, and none of the variables were assessed. However, during the pre- and the post-training dart-throwing tasks, the target was covered with a blank paper measuring 45 cm (wide) x 45.6 cm (height) reporting only the bullseye. After each throw, the dart's position was marked on the paper to assess the radial error. Similarly, during the pre- and post-training dart-throwing tasks were video-recorded to assess the range of motion and variability. At the end of the protocol, participants completed a 7-item questionnaire to assess tRNS side effects (i.e., skin sensation, fatigue, pain, headache, dizziness, tremors, and flashes). They rated these side effects on a 5-point Likert scale, ranging from 0 ("absent") to 4 ("strong"). At the end of the questionnaire, participants are asked to indicate whether they believe they received real or sham tRNS, in order to assess the effectiveness of the blinding procedure.

Table 1

Sex, age, darts expertise, and handedness of participants assigned to sham and hf-tRNS group.

	Sham (N=18)	hf-tRNS (N=19)
Sex (N Male, N Female)	15, 3	16, 3
Age (M, SD)	24.18, 5.88	26.26, 9.2
Darts expertise (Med, IQR)	0, 0-0	0, 0-1
Handedness (N Right, N Ambidextrous, N Left)	16, 1, 1	16, 1, 2

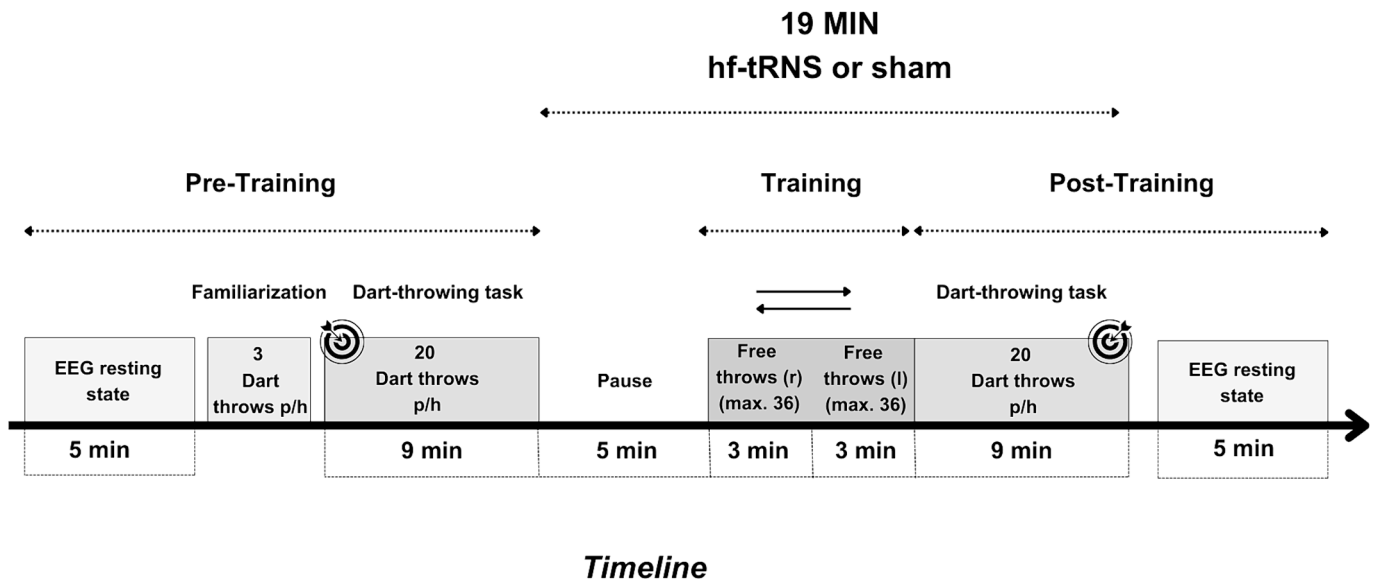


Fig. 1. Experimental protocol. The dart-throwing tasks sessions lasted longer than the training session, since after each throw the experimenter had to mark the dart's position on the covered target to assess radial error (see supplementary Fig. 1).

2.3. Apparatus

2.3.1. EEG data acquisition

A 32-channel Eego™ sports ANTneuro EEG system was adopted for EEG data acquisition at a sample rate of 500 Hz (ANT Neuro, Enschede, The Netherlands). The montage and amplifier setup were configured in a unipolar arrangement, with the CPz electrode serving as the common reference. The 30 scalp channels (and two mastoids) were positioned according to the international 10–20 electrode location system (see Fig. 2a).

2.3.2. tRNS administration

The stimulation was delivered by the Magstim DC-Stimulator Plus 0021, positioned behind the participant so as not to interfere with motor performance (see Fig. 2b). In the *verum* stimulation (hf-tRNS) a high-frequency random noise (100–600 Hz) current of 2.0 mA was delivered for 1140 s (including 60 s of fade-in and fade-out) through 2 rubber electrodes (4.3 cm x 4.3 cm) covered with conductive gel and positioned

bilaterally on the M1 (C3 and C4 electrodes). These parameters align with those suggested to enhance motor performance (Brancucci et al., 2023; Meek et al., 2021). The same parameters were used for the *sham condition*, but the current flow turned off after 60 s of fade-in.

2.4. Data processing

2.4.1. Behavioral data

Three dependent variables were measured during the pre- and post-training dart-throwing tasks: i) the mean radial error was assessed by measuring the distance of the dart (previously marked on the blank paper) from the bullseye in mm; ii) the mean (i.e., range of motion) and iii) the standard deviation (i.e., movement variability) of the arm movement performing the throws. Arm movement was assessed by analyzing the video record of the dart throws through the open-source software Kinovea (0.9.5 version) by measuring the angle (in degrees) formed between the shoulder and the wrist (vertex: elbow) in the maximum and minimum pre-throw extension movement (i.e., maximum

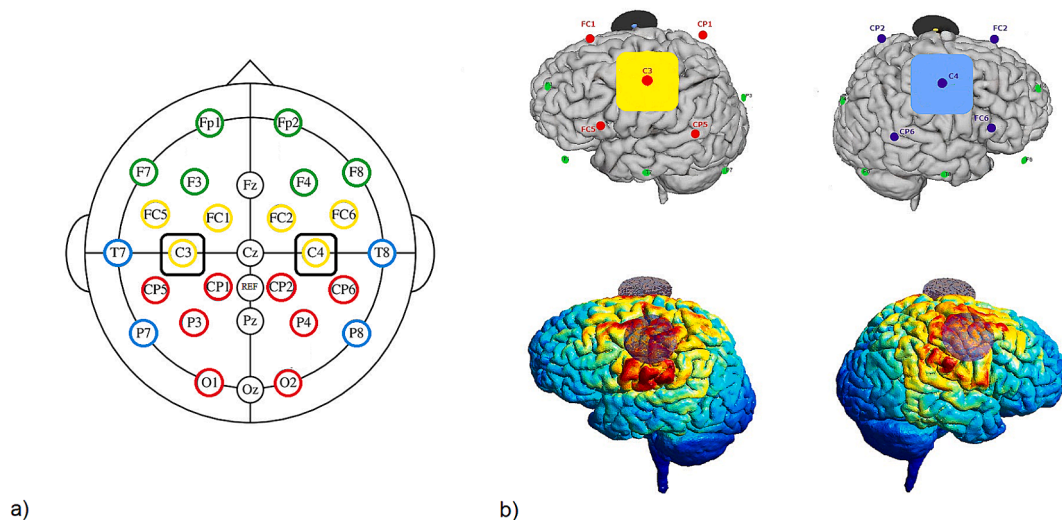


Fig. 2. EEG and tRNS montages. a) EEG data was collected through 30 scalp channels using CPz as the reference electrode. For analysis purposes, the electrode data was averaged within four clusters: the frontal cluster (green electrodes), central cluster (yellow electrodes), temporal cluster (blue electrodes), and posterior cluster (red electrodes). b) tRNS electrode placement (above) with current density distribution (below) estimated through SimNIBS (Thielscher et al., 2015).

amplitude - minimum amplitude). Lower radial errors indicate higher throwing accuracy, while higher range of motion and lower movement variability indicate more efficient and consistent movements. Finally, we measured the self-reported tRNS side effects by averaging the score assigned to each item.

2.4.2. EEG data preprocessing

EEG data processing was performed using EEGLab toolbox in Matlab 2023 (MathWorks Inc., USA). EEG data was first filtered using a high-pass filter of 1 Hz, and a low-pass filter of 45 Hz. Artifacts were removed using the automatic artifact rejection tool and then visually inspected. Afterward, noisy channels were interpolated, no more than three per data set, and data was referenced to an average reference. The mastoid electrodes (M1 and M2) were removed, resulting in 30 channels for analysis. The independent component analysis (ICA) was used to separate a multivariate signal into additive subcomponents and ICLabel, an EEGLab plugin used to distinguish independent components (ICs) as brain or non-brain sources, was applied to remove artifacts caused by muscle activity, heartbeats, eye movements, eye blinks, and other noises.

Subsequently, by using Brainstorm toolbox (Tadel et al., 2011), spectral EEG data were analyzed. EEG data baselines were normalized using the *scale with the mean* (dB) function ($x_{std} = 10 * \log_{10}(x/\mu)$). Welch's method was applied by averaging 1 s signal windows, with 50 % overlap calculated by using the Fast Fourier Transform (FFT) algorithm. Then, we computed the power spectral density (PSD) or periodogram for each subject in the five frequency bands (i.e., Delta (δ) = 2–4 Hz, Theta (θ) 5–7 Hz; Alpha (α) = 8–12 Hz; Beta (β) = 15–29 Hz, and Gamma (γ) = 30–45 Hz). Finally, we defined 4 clusters (see Fig. 2a) per hemisphere by averaging the respective electrodes: (i) Frontal (left: Fp1, F7, F3; right: Fp2, F4, F8); (ii) Central (left: Fc1, Fc5, C3; right: Fc2, Fc6, C4); (iii) Temporal (left: T7, P7; right: T8, P8); (iv) Posterior (left: Cp1, Cp5, P3, O1; right: Cp2, Cp6, P4, O2).

2.5. Data analysis

Data were analyzed using Jasp (0.17.2). The behavioral and EEG data distribution was assessed with the Shapiro-Wilk test. All data were normally distributed ($p > 0.05$), except for the tRNS side effect scores (all $p_s < 0.001$). Accordingly, parametric tests were used for all the variables repeated except for the side effect scores. The significance thresholds were set at $p < 0.05$. Additionally, due to the complexity of the mixed model analysis of variance (ANOVA), including both between and within factors, multiple comparisons were conducted for interaction effects only for $p < 0.05$ and $\eta^2 > 0.01$ and Holm's post hoc analyses were run for testing multiple comparisons.

Using as dependent variables the mean radial error, the mean arm movement (range of motion), and the arm movement standard deviation (movement variability), three 2*2*2 mixed-model ANOVAs (one for each dependent variable) were run using as between factor, the group (sham Vs. hf-tRNS) and as within factor the dart-throwing session (pre-training Vs. post-training) and the throwing arm (left Vs. right). The difference in experienced side effects between the sham and hf-tRNS group was assessed using 7 independent samples Mann-Whitney tests, one for each measure/item (i.e., skin sensation, fatigue, pain, headache, dizziness, tremors, and flashes). Additionally, the effectiveness of blinding was evaluated through a binomial test to determine whether participants' ability to correctly identify their assigned condition (sham Vs. hf-tRNS) differed significantly from chance.

Finally, using as dependent variables the rs-EEG power spectral density (rs-PSD) of the clusters, five (one for each frequency band) 2*2*4*2 ANOVA were run as between factor the group (sham Vs. hf-tRNS) and as within factor the recording session (pre-training, Vs. post-training), the cluster (frontal Vs. central Vs. temporal Vs. posterior) and the hemisphere (left Vs. right). When a significant interaction is found, the scalp current topographic distribution (in decibels) was

plotted by including all the electrodes.

Before running the analysis, outlier data (± 3 SD) were systematically identified within each condition of all the dependent variables and removed. Concerning the arm movement, 3 participants (1 assigned to the sham and 2 to the hf-tRNS) were not analyzed because of technical issues with video recording, while regarding the PSD three participants (all assigned to the hf-tRNS) were removed due excessive noise or the presence of more than three problematic channels in their EEG recordings.

3. Results

3.1. Dart-throwing performances

A 2*2*2 ANOVA on radial error data was run using the group as between factor and the dart-throwing session and the throwing arm as within factors. Results showed a main effect of the dart-throwing session ($F_{1,33} = 5.624$, $p = 0.024$, $\eta^2 = 0.013$; see Fig. 3a), with lower radial error during post-training and a main effect of the throwing arm ($F_{1,33} = 23.185$, $p < 0.001$, $\eta^2 = 0.099$), with lower radial error with the right arm. The 2*2*2 ANOVA on range of motion data showed a main effect of the dart-throwing session ($F_{1,30} = 24.425$, $p < 0.001$, $\eta^2 = 0.078$; see Fig. 3b) with a higher range of motion post-training and a main effect of the throwing arm ($F_{1,30} = 16.154$, $p < 0.001$, $\eta^2 = 0.049$), with a larger range of motion for the left arm. Furthermore, a significant group*throwing arm interaction was also found ($F_{1,30} = 7.057$, $p = 0.013$, $\eta^2 = 0.022$) (Fig. 4). Group*throwing post-hoc comparisons showed that for the left arm range of motion in the hf-tRNS group was larger compared with all the other conditions ($p < 0.005$). The 2*2*2 ANOVA on movement variability data showed no statistically significant effects (see Fig. 3c). The effects of the session on behavioral variables were reported in Table 2. Finally, the 7 Mann-Whitney tests run on each side effect measure showed no significant discomfort experienced by the sham group compared with the hf-tRNS group (see Supplementary Table 1). With an accuracy of 46 % (18 participants correctly identified their treatment condition, while 19 did not) the binomial test revealed no significant difference from chance levels ($p = 1.0$), indicating that participants were unable to reliably discern whether they received verum or sham tRNS.

3.2. rs-EEG PSD

The averaged whole brain (30 channels) spectrum (2–45 Hz) divided per group and recording session is reported in Fig. 5.

The ANOVA ran on δ showed a main effect of the cluster (frontal Vs. central Vs. temporal Vs. posterior) ($F_{3,96} = 15.758$, $p < 0.001$, $\eta^2 = 0.069$), and an interaction session*cluster ($F_{3,96} = 4.517$, $p = 0.005$, $\eta^2 = 0.004$) and no other statistically significant effect. Cluster posthoc comparisons showed that δ activity was significantly higher in the frontal cluster compared with the other three clusters ($p < 0.001$) and was lower in the temporal cluster compared with central ($p = 0.039$) and posterior ($p = 0.030$) clusters.

The ANOVA ran on θ showed a main effect of the recording session ($F_{1,31} = 4.574$, $p = 0.040$, $\eta^2 = 0.016$) with a lower θ power at post-training compared with pre-training, and no other significant effect (see Fig. 6).

The ANOVA ran on α showed a main effect of the cluster ($F_{3,93} = 7.923$, $p < 0.001$, $\eta^2 = 0.032$) a session*cluster interaction ($F_{3,93} = 3.720$, $p = 0.014$, $\eta^2 = 0.003$) and a group*recording session*hemisphere interaction ($F_{1,31} = 4.771$, $p = 0.037$, $\eta^2 = 0.001$). Cluster post-hocs comparisons showed a significantly higher posterior α power compared with the frontal ($p < 0.001$), central ($p = 0.048$) and temporal ($p < 0.001$) clusters.

The ANOVA ran on β showed a main effect of the group ($F_{1,31} = 11.172$, $p = 0.002$, $\eta^2 = 0.146$), a main effect of the cluster ($F_{3,93} = 30.670$, $p < 0.001$, $\eta^2 = 0.098$), a group*cluster interaction ($F_{3,93} =$

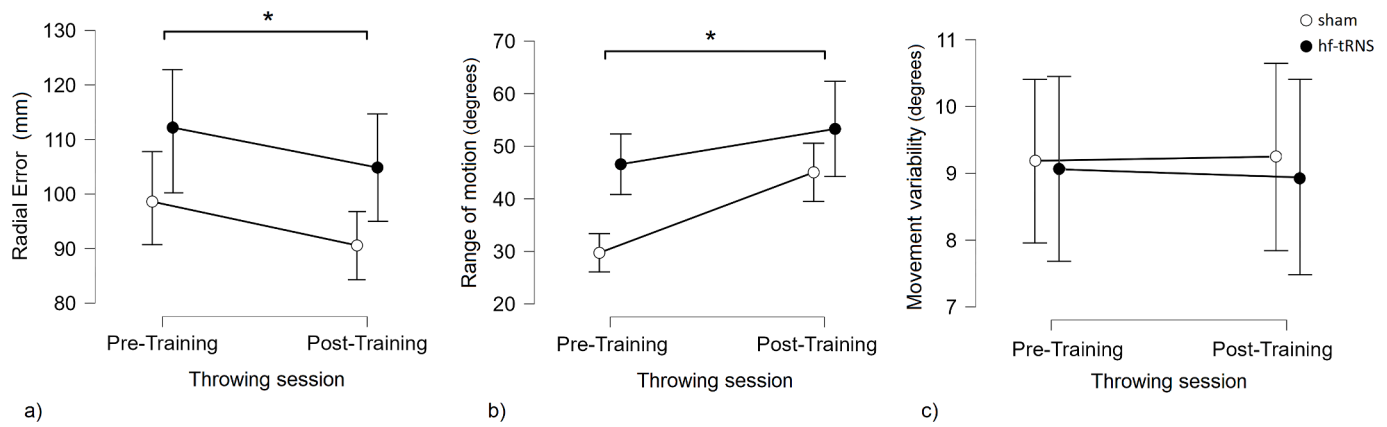


Fig. 3. Dart-throwing performance for sham and hf-tRNS group before (pre) and after (post) the training session. Training significantly affects both radial errors and range of motion while the group did not affect any behavioral variables: radial errors (a) significantly decreased after the training while range of motion (b) significantly increased after training. In contrast, movement variability (c) was not affected by the training session.

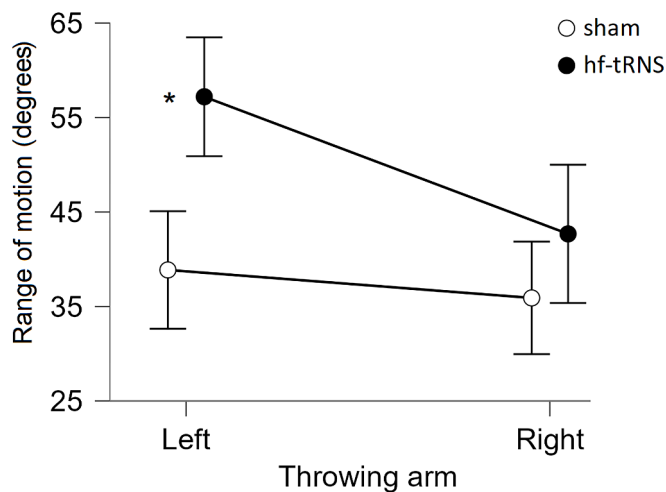


Fig. 4. Significant interaction between the group and the throwing arm. * Indicates that arm range of motion (in degrees using the elbow as vertex) with the left arm in the hf-tRNS group was greater than all the other comparisons. Data are reported as mean \pm confidence interval.

4.390, $p = 0.004$, $\eta^2 = 0.014$) (see Fig. 7), a group*session*hemisphere interaction ($F_{1,31} = 5.287$, $p = 0.028$, $\eta^2 = 0.001$) and a group*session*cluster*hemisphere interaction ($F_{3,93} = 4.906$, $p = 0.003$, $\eta^2 = 0.001$). The group*cluster post-hoc comparisons showed that frontal β PSD in the hf-tRNS group was lower compared with all the other conditions ($p < 0.003$), whereas posterior β power in the sham group was higher compared to all the other conditions ($p < 0.004$) except posterior and temporal sham.

Finally, the ANOVA ran on γ showed a main effect of the cluster ($F_{3,93} = 23.673$, $p < 0.001$, $\eta^2 = 0.108$), an interaction

session*hemisphere ($F_{1,31} = 4.229$, $p = 0.048$, $\eta^2 = 0.002$) and an interaction cluster*hemisphere ($F_{3,93} = 2.752$, $p = 0.047$, $\eta^2 = 0.001$) and no other effect. Cluster post-hoc comparisons showed a higher γ power in the temporal cluster compared with the frontal ($p < 0.001$), central ($p = 0.012$), and posterior ($p < 0.001$) clusters. Further central γ power was higher in the central cluster compared with the frontal and posterior clusters ($p < 0.001$).

The comparisons between the clusters' power for each frequency band are reported in Table 3.

4. Discussion

In this study, neurobiology meets motor skills research by examining the neural mechanisms involved in fast learning and exploring the enhancement of visuomotor skills through tRNS. Particularly, we explored the combined effects of a single dart-throwing training session and hf-tRNS on dart-throwing performance and rs-EEG PSD. Following our H1a, throwing performance, assessed as radial error, and arm range of motion were both enhanced after the training. On the other hand, movement variability has not been modulated by our single session of dart-throwing training. Contrary to our H1b, dart-throwing performance has not been modulated by hf-tRNS. Regarding the rs-EEG data, we found that β - and γ - PSD were mainly distributed in the temporal cluster, whereas δ in the frontal and α in the posterior cluster, respectively. More interestingly, motor training resulted in a generalized decrease in θ power but had no other effect, with no hf-tRNS effect on rs-EEG PSD. Participants did not report any intolerable sensation requiring tRNS interruption, and the side effects scores were low and comparable between the sham and hf-tRNS groups, demonstrating the feasibility and good tolerability of the hf-tRNS.

4.1. Effects of motor training and hf-tRNS on dart-throwing performance

Our data indicates the presence of a learning effect after the dart-

Table 2

Main effect of throwing session and throwing arm factors on throwing radial error, movement variability, and variability. While radial error and arm range of motion were lower at the post-training (compared with the pre-training) session and when performed with the right arm (compared with the left), none of these main effects were found for arm movement variability.

Throwing session	Radial error (mm)			Range of motion (degrees)			Movement variability (degrees)		
	Mean	SD	p-value	Mean	SD	p-value	Mean	SD	p-value
Pre-training	105.40	33.69	0.024	38.16	18.00	< 0.001	9.13	3.46	0.923
Post-training	97.71	29.17		49.17	15.15		9.10	2.84	
Throwing arm	Mean	SD	p-value	Mean	SD	p-value	Mean	SD	p-value
Left	112.17	33.38	< 0.001	48.03	19.33	< 0.001	9.43	3.49	0.227
Right	90.94	29.48		39.30	13.82		8.80	2.81	

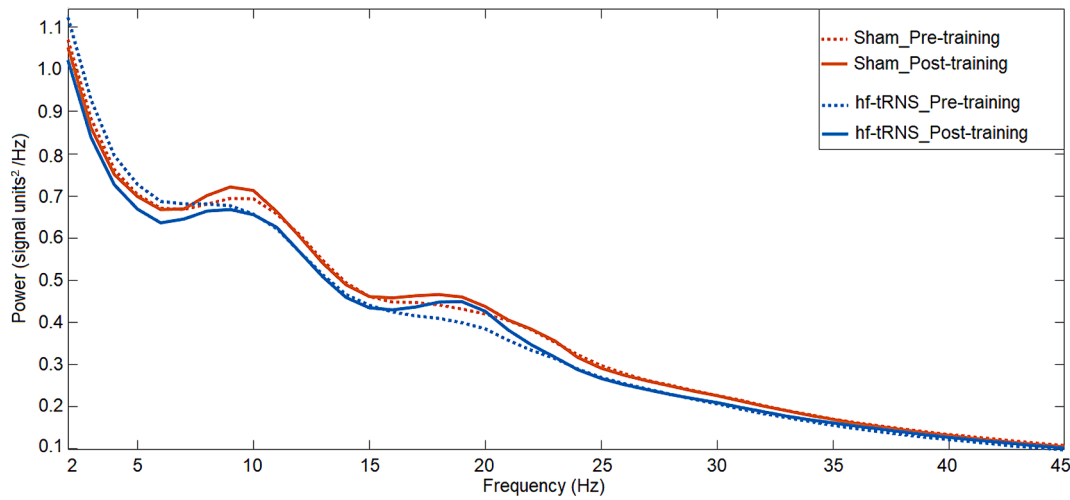


Fig. 5. Whole brain (all channels) rs-EEG PDS (2–45 Hz). Different lines indicate the four different conditions.

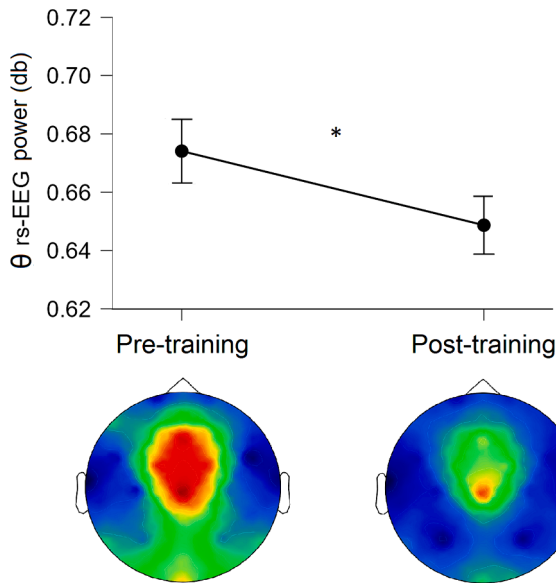


Fig. 6. Significant main effect of the recording session on θ normalized power (in normalized decibel units). The graph and the topoplots show lower θ power after the training. Data are reported as mean \pm confidence interval.

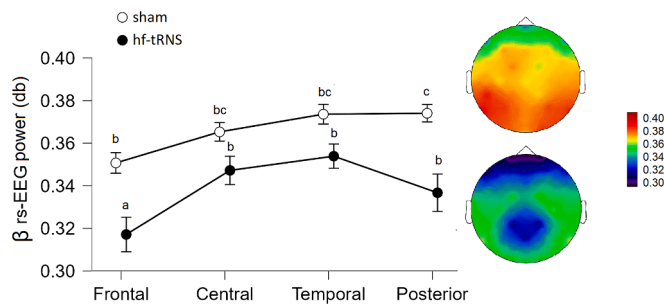


Fig. 7. A significant interaction between group and distribution in the whole brain of β θ normalized power (in normalized decibel units). The graph and the topographic plots report the significantly lower β power in the frontal and posterior cluster of the hf-tRNS group compared with the sham group. Data are reported as mean \pm confidence interval.

Table 3

Cluster's normalized power for each EEG band (in in normalized decibel units). Different letters indicate significant differences within each frequency band cluster.

	Delta (δ)	Theta (θ)	Alpha (α)	Beta (β)	Gamma (γ)
<i>Cluster</i>	<i>Mean (SD)</i>	<i>Mean (SD)</i>	<i>Mean (SD)</i>	<i>Mean (SD)</i>	<i>Mean (SD)</i>
Frontal	1.026 (0.222) a	0.651 (0.113) a	0.629 (0.109) a	0.334 (0.033) a	0.146 (0.022) a
Central	0.876 (0.168) b	0.659 (0.096) a	0.645 (0.079) a	0.356 (0.026) b	0.156 (0.020) b
Temporal	0.830 (0.155) c	0.635 (0.103) a	0.630 (0.088) a	0.364 (0.025) c	0.163 (0.024) c
Posterior	0.881 (0.150) b	0.645 (0.101) a	0.670 (0.086) b	0.355 (0.037) b	0.146 (0.018) a

throwing training. Particularly, both radial error and arm range of motion have been improved after the training. It is well-known that practice and repetition of a task promote neuromotor adaptations such as skills acquisition and accuracy improvement (Meek et al., 2021). Mousavi et al., (2019) investigated the relationship between learning a dart-throwing task and virtual training. They demonstrated a reduction in mean radial error compared to the pre-test phase. Similarly, in the study by Tirp et al., (2015), a significant effect of fast training on throwing accuracy was evident between the pre- and post-throwing tasks. Consistent with the existing literature, our study revealed an improvement in throwing accuracy following training, which is indicative of fast learning (rapid and transient improvements), typical of isolated tasks such as a game of pool or darts (Meek et al., 2021). The latter requires precise coordination of fingers and upper limb joints and dynamic body stabilization to prevent mistakes during the throw (Meek et al., 2021): we also observed an increase in range of motion, which aligns with studies reporting movement and timing optimization after a session of motor-visual training (Nasu et al., 2014; Loosh et al., 1999); an optimized global performance has been proved to be the result of a rapid adaptation of the speed-accuracy trade-off, leading to a refined throw (Lefebvre et al., 2012). On the other hand, despite some studies suggesting a reduction in throwing timing and an increase in movement consistency due to fast learning (Shmuelof et al., 2012), we did not observe an arm movement variability decrease after the training. Bao et al., (2016) showed that expert darts players exhibited more stable dart-throwing movements than novices. The ability to maintain a fixed elbow position during the throw was identified as a significant skill in the context of dart-throwing but might be more acquired after slow motor training. Congruently, in our study, a single session of dart-throwing training (fast motor learning) has not been sufficient to

observe arm movement stabilization, although increasing in range of motion was observed.

Additionally, the right arm exhibited greater throwing accuracy (i.e. reduced both radial error and range of motion), which reflects the predominantly right-handedness of our sample. Movement variability, instead, was the same between the left and right arm, confirming that such motor skill relies on different neuromotor patterns compared to throwing accuracy and range of motion. Further analysis of intragroup differences in arm range of motion revealed a higher range of motion of the left arm than the right arm in the hf-tRNS condition and no difference in the sham-tRNS group. This effect, which was not affected by the throwing session, can be attributed to intrinsic differences between the samples, even though participants' handedness and expertise were equally distributed between the sham and hf-tRNS groups.

Hf-tRNS did not affect either radial error or arm movement. There have yet to be any experiments in which this technique has been applied to the study of motor learning in a dart-throwing task. Therefore, H1b was based on hf-tRNS effects on brain plasticity and M1 excitability (Brancucci et al., 2023). Hf-tRNS seems to be an effective method for increasing cortical excitability in the M1 (Inukai et al., 2016), as proved by an increase in motor-evoked potential amplitude (Terney et al., 2008). However, different stimulation durations or combinations of tasks can lead to different outcomes (Chaieb et al., 2009). For instance, Tommasi et al., (2015) investigated the effect of hf-tRNS administered over the right parietal and left frontal areas, on the performance of a skilled air-shooting. During the hf-tRNS the performance of the shooter was improved. The authors suggest that tRNS could affect cognitive resources and arousal, which are fundamental for a good shoot. On the other hand, de Albuquerque et al., (2019) examined the interaction between tRNS, motor learning, and retention in young adults who completed a session of golf putting practice. They observed that hf-tRNS over the motor cortex did not influence performance, indicating limited effectiveness in promoting the acquisition or retention of motor skills. The effectiveness of tRNS could benefit from further research involving the modulation of various stimulation parameters, the study of different sports, and a more in-depth evaluation of individual differences (e.g., the expertise) that can influence its effect.

4.2. Effects of motor training and hf-tRNS on rs-EEG PSD

For explorative purposes, we assessed whole brain rs-EEG PSD for each frequency band. While there is no effect of tRNS on rs-EEG PSD, different studies have explored the impact of visuomotor training and motor learning on rs-EEG PSD with contrasting results. Our data revealed that dart-throwing training determines a decrease in θ power, while the training did not affect the other frequency bands' power. On the other hand, the tRNS of M1 did not modulate any frequency band power, neither in the central cluster including the motor and premotor cortex, in which most of the current flows and is responsible for the LTP-like mechanism involved in fast motor learning.

Theta (θ) waves are known to play a crucial role in motor control. For instance, an increase in θ power has been observed in the contralateral motor area during the onset of fast ballistic movements (Ofori et al., 2015). Additionally, θ waves are synchronized with movement onset, and θ correlates with movement acceleration (Ofori et al., 2015). Cognitive processes, such as attention, perception, and visuospatial processing, as well as the type of task, should be considered when analyzing PSD data (Antonenko et al., 2016). Specifically, α and θ oscillations are key indicators of cognitive load and task difficulty. Research has shown that during more complex tasks, such as spatial working memory challenges, there is an increase in α power and a corresponding decrease in θ power when compared to simpler tasks (Gevins and Smith, 2000). This pattern suggests that α and θ oscillations play a crucial role in the brain's response to varying levels of cognitive demand. In addition to this, θ activity within motor cortical regions has been specifically associated with the consolidation of motor learning,

implying that these oscillations may help solidify new motor skills (Meissner et al., 2018). Therefore, it is reasonable to hypothesize that as an individual becomes more proficient in a motor skill, the cognitive load required for its execution diminishes. This reduction may be reflected in the observed decrease in θ power following training, particularly in the medial brain regions. This decrease is likely a sign that the visuomotor skills have been successfully learned, allowing for more efficient neural processing during motor task performance. The topographic plot highlights that most of the decrease of θ activity took place within all the medial and dorsolateral sensory-motor and prefrontal cortex. These extended regions are involved in both visuomotor skill and learning and particularly, the dorsal posterior parietal cortex and the supplementary parietal lobule, which are involved in spatial orientation, attention (Horn & Adamczyk, 2012), and visuomotor integration (Culham, 2015). They also encompass the dorsal portion of the primary somatosensory and M1 (including the arms somatotopic representation; Schellekens et al., 2018), the SMA, and the dorsolateral prefrontal cortex, which is associated with motor learning, movement control and executive functions (e.g., Ghilardi et al., 2000; Zgaljardic et al., 2010). In the context of visuomotor learning, a decrease in θ waves in such regions after a single dart-throwing training session may indicate a reduction in the cognitive load associated with the dart-throwing task. This reduction is likely a result of rapid learning, which leads to the streamlining and automation of the throwing motion.

There are, however, contrasting findings regarding the relationship between β band oscillations and motor learning (Boonstra et al., 2007; Houweling et al., 2008). In fact, while some authors reported increased cortical activity in the β band during motor learning (Henz et al., 2018; Kiefer et al., 2014) others observed a decrease (Pollok et al., 2014; Gutiérrez & Ramírez-Moreno, 2016), or no significant changes in β activity after motor training (Zhu et al., 2010). Similar to this latter finding, we did not observe any effect of the training on β band PSD in any brain cluster. Despite that, as occurred for the arm range of motion, the hf-tRNS group showed lower β power in the frontal and posterior clusters than the sham group, independently by the throwing session. As for the range of motion, we suppose that this effect is due to interindividual differences between the groups. In addition it is worth noting that when using all the EEG channels, such an effect did not reach statistical significance.

After fast learning, some studies observed that the frontal area exhibits an increase in δ activity (Schneider et al., 2010) and a decrease in α activity (Ohmatsu et al., 2014). This brain region involves various cognitive functions, including executive control and spatial memory (Bubb et al., 2018). Δ oscillations are also implicated in memory tasks (Harmony, 2013), which, in turn, can be influenced by physical exercise (Smith et al., 2010). Currently, this connection remains largely speculative, and our data did not confirm any of such speculation. On the other hand, γ waves are involved in the integration of sensory information and the association of complex neural patterns. During a motor task, γ power can vary based on task complexity. For instance, while a γ increase has been observed following complex training (Aliakbaryhosseinabadi et al., 2021), our motor training had no effect on slow- γ waves (30–45 Hz). Given our primary focus was on motor coordination and motor skill learning, which typically does not involve complex processing involving temporal information or the integration of multisensory stimuli, this is an expected outcome.

The above-mentioned literature shows inconsistencies in this field, where the relationship between the PSD of rs-EEG frequency bands and motor training remains inconclusive (Aliakbaryhosseinabadi et al., 2021). On the other hand, we observed a whole-brain PSD characterized by a predominance of low-frequency oscillations (δ and θ) over high-frequency ones (β and γ). Focusing on the distribution of each frequency band in the 4 brain clusters, we found higher δ power in the frontal region (and lower in the temporal region), higher α power in posterior regions, and higher β and γ power in the temporal region (and lower in the frontal cluster). These are common PSD patterns observed

during healthy individuals' rs-EEG (Niedermeyer and Silva, 2005; Popov et al., 2023) that suggest the reliability of our data.

In the context of this study, no significant effects of hf-tRNS on PSD have been observed in any frequency band, which is congruent with the lack of modulation on behavioral (throwing) performance. The lack of effects of hf-tRNS on rs-EEG PSD matches the results of a recent methodological study exploring the frequency-specific effect of tRNS on resting-state EEG data spectrum, observing no influence on any frequency band (Ke et al., 2024).

4.3. Limitations, further research, and conclusion

Although this is the very first research to investigate both the behavioral and neurophysiological effects of single-session dart-throwing training combined or not with M1 hf-tRNS and despite the relatively large sample size compared to similar studies in this field, this work is not without limitations.

Firstly, from a methodological perspective, using a parallel design, with two subsamples assigned to the sham or verum tRNS condition, was unsuccessful. Despite the careful distribution of participants, based on key criteria such as manual dexterity and expertise in the game of darts, the two groups exhibited significant interactions in range of motion and β power. Such effects could have been mitigated by employing a cross-over design. Future studies could replicate our protocol using a within-subject design. A further limitation is the single-blind design. Although a double-blind approach would have been ideal, it was not feasible in our study due to the transcranial stimulation device, which did not allow for blinding the stimulation parameters to the operator. Another issue is the absence of a control group receiving no motor training to analyze the differences in PSD between the trained and non-trained groups. We suggest that the decrease in θ power is due to motor learning from dart-throwing training, but we cannot compare this data with a sample receiving no training at all. Given that the study of the effect of single darts training and fast motor learning on rsEEG PSD is inconclusive, future studies should delve deeper into these aspects. One additional limitation is that our sample consisted predominantly of males (31 out of 37). While this imbalance may limit the generalizability of our findings, it is important to note that it reduced variability in the data, potentially increasing the likelihood of detecting an effect of tRNS if one existed. Future studies should, however, investigate potentially sex-dependent effect with larger and sex-balanced sample sizes. Furthermore, the applicability of tRNS in sports as a training aid is an innovative field that requires more attention. Several parameters of tRNS, such as the frequency range of noise, the site of stimulation, and the current intensity, could be adjusted to optimize the motor and neural effects of tES. Our research has the strength of being the first to investigate the after-effects of tRNS stimulation on rs-EEG PSD. Since we found no effect of tRNS on rs-EEG PSD, future studies should explore the effects of such parameter modulation on both motor training and performance, as well as on other EEG measures such as brain connectivity.

In summary, this study revealed that a single session of dart-throwing training improves throwing precision and motor effectiveness (i.e., radial error and arm range of motion) but not consistency (i.e., movement variability). Additionally, our findings indicate that after motor training, rs-EEG θ power oscillation decreases, while the power in other frequency bands (δ , α , β , and γ) remains unaffected by the training. The application of hf-tRNS over the M1, although well tolerated, did not modulate any of these effects. Future research may consider other sports and/or implement longer stimulation protocols to refine the understanding of long training and multi-session hf-tRNS effects on the sensorimotor cortex in the context of slow learning and training support. Additionally, investigating motor learning and tES effects using alternative measures, such as functional connectivity, could provide deeper insights. Finally, as research progresses, it is essential to address the ethical considerations of neurodoping, ensuring that the benefits of tES outweigh the potential risks (Friebs et al., 2022). Although tES appears

relatively safe when used according to established standards (Bikson et al., 2009; Farah et al., 2004; Woods et al., 2016), potential long-term neurophysiological effects, particularly in unregulated contexts, should be thoroughly investigated.

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CRedit authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.brainres.2024.149249>.

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