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ORIGINAL ARTICLE

Retention following a short-term cup stacking training: Performance and electrocortical activity

Amélioration des habilités après une séance d'entraînement au cup stacking : performances et activité électrique corticale

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Cup stacking ;
Training ;
Retention ;
EEG ;
Motor control

Summary
Objective. — The aim of this study was to describe training-related changes in brain activation immediately after, 24 hours and 7 days after a single cup stacking training session.
Methods. — Twenty-two young adults were divided into a training and a control group. Both groups performed five attempts of a cup stacking task before and after 20-minutes of cup stacking training (control group were resting). Both groups were re-tested 24 hours and 7 days after the training session. Scalp electroencephalography was recorded from electrodes located on the frontal, central and parietal brain regions. The electroencephalography absolute power was computed for electrodes across each region.
Results. — There was a substantial reduction in the time to complete cup stacking for the training group ($35 \pm 18\%$, $p < 0.001$), whereas the control group also improved over time ($18 \pm 3\%$).

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Moreover, there was an overall reduction on the alpha and beta power for the frontal, central and parietal brain regions following the 20-minute training/rest across both groups. Both alpha and beta power returned to pre-test levels 24 hours and 7 days following training.
Conclusion. — A 20-minute cup stacking training significantly improved cup stacking performance. However, the brain-related adaptations to training were not retained when measuring EEG 24 hours or 7 days following training.

MOTS CLÉS
Empilement de gobelets ;
Entraînement ;
Rétention ;
EEG ;
Contrôle moteur

Résumé
Objectif. — Le but de cette étude était de décrire les réponses de l'activation cérébrale, immédiatement après, 24 heures et 7 jours à la suite d'une seule séance d'entraînement au ''cup stacking'' (sport d'empilement rapide de tasses spécialement conçues à cet effet).
Méthodologie. — Vingt-deux jeunes adultes ont été divisés en un groupe entraîné et un groupe témoin. Les deux groupes ont effectué cinq tentatives d'un exercice test de cup stacking, avant et après 20 minutes d'une séance entraînement à ce sport (alors que le groupe témoin se reposait). Les deux groupes ont été retestés 24 heures et 7 jours après la session d'entraînement. Un électroencéphalogramme de surface (EEG) a été enregistré à partir d'électrodes situées sur les régions frontales, centrales et pariétales du cerveau. La puissance absolue du signal EEG a été calculée pour les signaux spécifiques de chaque région cérébrale.
Résultats. — Il y a eu une réduction substantielle du temps mis pour réaliser chaque tâche de cup stacking dans le groupe entraîné (35 ± 18%, P <0,001), tandis que le groupe témoin a également amélioré ses performances (18 ± 3%). De plus, il y avait une réduction globale de la puissance alpha et bêta du signal EEG dans les régions frontales, centrales et pariétales dans les 20 minutes qui suivent la séance d'entraînement, et ce dans les deux groupes de sujets. La puissance alpha et bêta du signal EEG revient aux niveaux pré-test 24 heures et 7 jours après l'entraînement.
Conclusion. — Une seule séance d'entraînement de 20 minutes a considérablement amélioré les performances au cup stacking. Cependant, les réponses adaptatives corticales ne sont que temporaires, le signal EEG étant normalisé 24 heures et 7 jours après la séance d'entraînement.

1. Introduction

Effective sports performance requires extensive training of motor skills, which can reach high level of refinement in high-level athletes [1]. Performance improvements are associated with neural adaptations to automatize goal-directed movements, subsequently reducing the need for constant performance monitoring. The motor learning process has been divided previously in cognitive, associative and autonomous stages, which can also reach performance plateaus in highly trained individuals [2,3]. It has previously been shown that an acquired motor skill can be performed accurately even following long periods of non-practice [4]. Conversely, highly refined movement patterns performed by musicians and elite athletes require frequent practice to maintain high performance levels [4,5]. Therefore, some aspects of a learned motor skill might be forgotten, and some are well retained [4].

Bridging the gap between behavioural neuroscience and practical sports-related motor behaviour is highly relevant to understanding motor learning and performance [6]. In mice, retaining a motor skill requires neural plasticity, through increases in dendritic spines that allow the generation of the control pathway [7]. Studies using brain imaging revealed that short-term practice reduced brain activity in cortical (prefrontal cortex, left presupplementary motor area, the right inferior and bilateral superior parietal lobules, the left precuneus, and right inferior temporal gyrus) and subcortical areas (right posterior cerebellar cortex), while there were increases in cortical areas such as primary motor cortex (M1), the left supplementary motor area, left premotor cortex, left posterior cingulate cortex, bilateral precuneus, and the left middle occipital gyrus. Subcortically, increases in the left globus pallidus, the right thalamus, and the anterior and posterior cerebellar cortex also occur [8]. It is noteworthy that brain activity in all studies cited by Lohse et al. (2014) were conducted using magnetic resonance imaging (MRI) or positron emission spectroscopy (PET) scanning, limiting the motor task to simple movements as these techniques restrict mobility. Therefore, such literature might not fully represent learning-related changes in brain activation in realistic learning contexts.

Surface electroencephalography (EEG) is a technique to record electrocortical activity that allows free movements during recordings and has been increasingly used in sports [9]. Learning a motor skill reduces the alpha power (8—12 Hz) in brain regions related to motor control and sensorimotor integration [10—12]. Likewise, there are reductions in the spectral power at the beta band (13—30 Hz) in these same brain areas following a motor learning activity [13,14]. Moreover, increased engagement to perform a golf-putting task requires increased EEG power in beta and alpha waves in the frontal brain region [6]. It has recently been shown that both young and older adults can present with reductions in alpha and beta spectral power following a training program consisting of four sessions [15]. However older adults presented with lower power as compared to younger counterparts. Therefore, EEG has been a relevant tool to investigate motor learning in practical conditions and must be further explored to expand our knowledge on performance improvements in sports.

Sports actions often demand the control of multiple body segments guided by visual information. A highly relevant example of such an action is the cup stacking competition, where athletes must handle positioning cups in several sequences bimanually. The competition is won by the athlete performing the stipulated sequence in the shortest time, therefore, hand-eye coordination and movement refinement are of utmost importance [16,17]. Hand-eye coordination is in turn an expression of accuracy [18,19]. Cup stacking has been shown to have a positive influence on these particular parameters [17], but there is no knowledge on the short-term cortical adaptations to performing cup stacking. Moreover, potential adaptations occurring during the execution of such complex motor task is yet to be shown. Therefore, the aim of the current study was to describe the training-related changes in brain activation immediately following, 24 hours after and 7 days after a short cup stacking training session. It was hypothesized that 1) the training group would show overall reductions in the alpha and beta power in brain areas related to motor control (motor and supplementary motor area), and somatosensory control (parietal area) from Pre- to Post-test, 24 hr and 7 days after training; 2) the training group would show an overall increase in the alpha and beta power in brain areas related to motor planning and attention (pre-frontal cortex) from Pre- to Post-test, 24 hr and 7 days after training.

2. Methods

2.1. Participants

Twenty-five healthy young individuals, without known neurological impairment participated and were randomly assigned to either a control or a training group. Three participants withdrew their participation during the experiment, thus leaving a total of 22 participants ($n = 12$ for the training group (9 males, 3 females) and $n = 10$ for the control group (8 males, 2 females)) eligible for final data analysis (17 males and 5 females; age: 22.86 ± 2.05 years; height: 178.5 cm; weight: 79.2 kg). Inclusion criteria for this experiment were: no known neurological impairment, no previous musculoskeletal disorders in the upper limbs and shoulders. Previous experience with the cup stacking exercise was defined as an exclusion criteria, to minimize the effect of previous experience on the research outcomes. All participants provided written informed consent before participation and the procedures were in accordance with the ethical committee of Northern Jutland practices.

2.2. Experimental Design

The experiment consisted of four tests; Pre-test, Post-test, 24-hour retention (R1) and 7-day retention (R2), as shown in Fig. 1. In each test, participants performed five attempts to complete a cup stacking task, while surface EEG was recorded throughout the entire attempt. The training group executed a 20-minute training period between the Pre-test and Post-test, in which they continuously performed the proposed cup stacking task. Participants in the training group were instructed to practice the cup stacking task aiming to improve task time as much as possible, while taking rest periods between attempts if necessary. To minimize changes in arousal and interferences in the consolidation during the 20-minute resting period [20], participants on the control group were engaged into dialogues with the experimenters. The Dialogues were standardized to be addressing the hobbies and other activities that participants enjoy doing during their free time. This activity also assured that participants used the resting period to generate strategic considerations on how to perform the cup stacking task in the Post-test. All participants repeated the five attempts of cup stacking twenty-four and seven days after the training/rest session, from which performance and surface EEG were recorded.

2.3. Cup stacking task

All testing and training were performed using a WSSA approved speed stacking set consisting of 12 cups and a mat with a timer (Speed Stacks, Inc., Castle Rock, CO), and a table with adjustable height that participants set individually. The table height was replicated for all participants throughout the test days. Initially, the cups were placed in front of the participant with a three-cup tower on the left, a six-cup tower in the middle, and a three-cup tower on the right (Fig. 2A). Participants should have their hands on a pressure-sensitive mat until a green light was shown. The task was to ''up-stack'' the cup towers into a 3—6—3 formation (Fig. 2B) and ''down-stack'' them back into the starting-position (Fig. 2C) as fast as possible. After completion of each trial, participants had to bring their hands back on top of the pressure sensitive mat.

Cup stacking performance was measured by using a pressure mat that computed the time from start to finish of the stacking task. Participants were required to start ''up-stacking'' from left to right and ''down-stack'' from left to right again. No instructions regarding handling technique or strategies to perform the task was given by the experimenters. During the training session, the time to complete the trials, and the total number of trials, were recorded from all trained participants. To avoid physical and mental exhaustion during training, participants were allowed to rest for 60—90 seconds whenever necessary. As improvement in cup stacking performance should lead to a reduced time to finish the task, a training improvement index was computed by calculating the difference between time to complete the first and the last five cup stacking trials. Higher improvement indexes would suggest shorter time to perform the cup-stacking task.

2.4. EEG recordings

The electrocortical activity during the cup stacking trials was recorded using a wireless active wet EEG system (g.Nautilus 32, g.Tec, Schiedlberg, Austria) sampled at 500 Hz. The EEG signals recorded throughout the experiment were segmented from the start of the cup stacking trial (e.g., moving the hands out of the pressure sensitive mat)

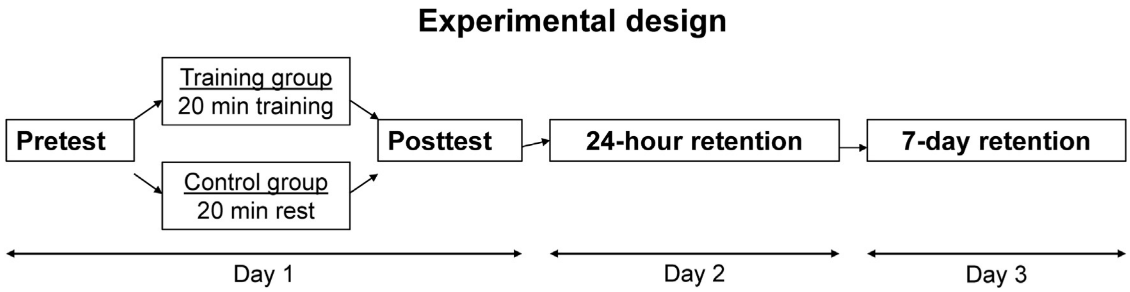

Figure 1 The experimental timeline.

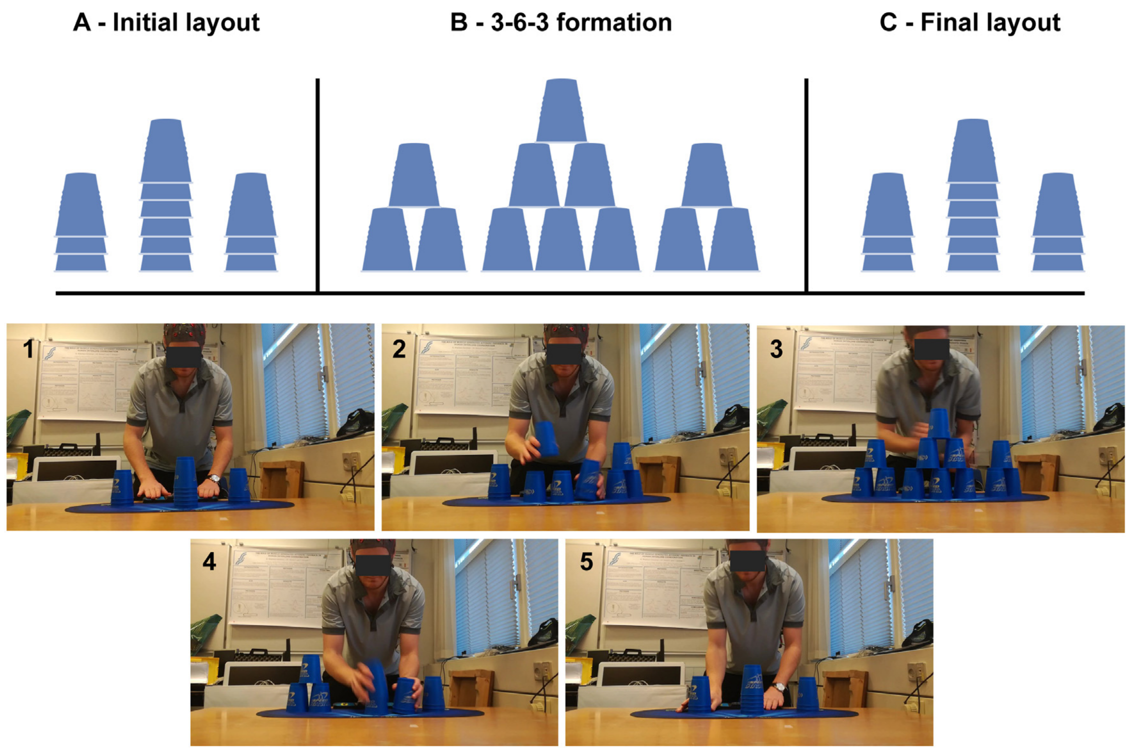

Figure 2 The 3—6—3 formation in cup stacking. A: is the starting position; B: the up-stacked position and; C: the down-stacked position. The bottom figures from 1 to 5) demonstrate a sequence performed by a participant using the EEG cap and the cup stacking setup.

to touching the pressure sensitive mat again after finishing. The recorded channels were Fp1, Fp2, AF3, AF4, F3, Fz, F4, FC1, FC2, C3, Cz, C4, CP1, CP2 and Pz. A reference electrode was placed on the right earlobe. The electrode location followed the 10—20 system. On each test day, a 30-second resting-state recording was conducted prior to the conduction of the cup stacking protocols.

2.5. EEG data processing

All processing and analysis were performed in Matlab (R2014a, MathWorks, Inc. Massachusetts, USA) using scripts based on EEGLAB 13.6.5b [21]. Initially, the five individual cup stacking trials were concatenated for the same test (Pre-test, Post-test, 24-hour or 7-day retention). Subsequently, this single dataset was band-passed using finite impulse response (FIR) filter between 4—80 Hz, and also filtered for removing line noise (50 Hz) using the Cleanline technique in EEGLAB (https://www.nitrc.org/projects/cleanline/). The band-pass filter from 4 Hz was intended to minimize the effects of the considerable amount of upper body and head movements during the cup stacking task. The next step was channel rejection using the following methods:

- channels with magnitude < 30 or > 10000 µV;
- channels with kurtosis > 5 standard deviation from the mean;
- channels uncorrelated with the surrounding channels ($r <$ 0.4) for more than 1% of the total time;
- channels with standard deviation substantially higher than the other measured channels [22,23].

The next step was to visually inspect and remove EEG data sectors presenting substantial artifacts from all remaining channels. The merged and cleaned datasets were re-referenced to the average across channels. Subsequently, independent component analysis was performed on these data-sets to identify and remove eye blinks [24,25] and artifacts related to muscle activity [26]. On average, 1.7 ± 0.3 artifactual components were removed from the EEG datasets. Following the rejection of specific independent components, the remaining independent components were back projected to the EEG channels.

2.6. EEG data analysis

Four channels (Fz, Cz, CP1 and CP2) were present for all participants across all datasets after data cleaning, and were maintained for further analysis. The channels not used in the analysis were relevant for maximizing the quality of independent component analysis in capturing data variability related to various types of EEG artifacts. Channel Fz is located over the prefrontal cortex, which is associated with motor planning [27,28]. The channel Cz is located over the motor area (M1), which has been associated with motor control and consolidation stage of learning [28,29]. Channels CP1 and CP2 are located over the sensorimotor cortices, which is associated with movement monitoring and control [30].

The power spectrum from the resting-state EEG files and the cup stacking trials were computed (Hanning windowing,1024 ms FFT, 512 ms point window). Subsequently, the absolute power was quantified for the alpha (8—13 Hz), beta (13—30 Hz) and gamma bands (31—50 Hz) for all tests. The absolute power from channels CP1 and CP2 were averaged to represent the parietal area. The averaging of these electrodes is justifiable as there is a high symmetry in brain activation during bimanual tasks such as cup stacking [31]. Finally, the resting-state EEG recording for these channels was used to normalize the cup-stacking data across different participants and test days. For each channel, the EEG power during resting state was computed for the alpha, beta and gamma bands. Subsequently, the power from each band from a given EEG channels was normalized by the respective power from the resting state EEG (% resting state).

2.7. Statistical Analysis

The software SPSS (version 25, IBM, Chicago, IL, USA) was used for all statistical analysis. A Shapiro-Wilk test was conducted and confirmed that the data of the different test days was normally distributed. Two-way analysis of variance (ANOVA) with repeated measures was used to assess the effect of group (control *vs* training) and time (Pre-test *vs* Post-test *vs* 24-hr *vs* 7-day) on the cup stacking time and EEG absolute power from the different cortical areas and frequency bands. Partial eta-squared (ηp^2) were computed for all ANOVA calculations. Compound symmetry, or sphericity, was verified by the Mauchly's test. If necessary, a Bonferroni Post-hoc test was performed to specify statistical differences within time points. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. In addition, Pearson correlation coefficient was calculated between the number of cup stacking attempts the trained participants performed during training and the difference in the time to complete from Pre- to Post-test. The rationale for this correlation was to assess whether the number of cup stacking repetitions during training could in fact lead to reductions in time to complete the cup stacking at the end of the training program. The significance level was set to $p < 0.05$. the p-values between 0.05 and 0.1 were considered trends. Data was reported as mean $\pm$ standard deviation.

3. Results

3.1. Cup stacking performance

A significant time x group interaction ($p < 0.005$; $F(3,60) = 5.148$; $\eta p^2 = 0.205$) was found in performance when comparing the training group and control group over the course of the experiment (Fig. 3A). Post-hoc analysis revealed that both groups had similar performance in the Pre-test, but the training group was faster than the control group in the Post, R1 and R2 ($p < 0.005$). Moreover, there was a significant correlation between the performance improvement index (ie., the delta time between the first five and last five cup stacking trials during training) and the total number of trials performed ($r^2 = -0.55$, $p < 0.01$, Fig. 3). Therefore, training participants presenting the greatest improvements in time to complete the cup stacking task were those performing the lowest amount of trials during training.

3.2. EEG measurements

Frontal channel (Fz). There was a significant main effect of time on the absolute power for the alpha and beta bands (alpha (Fig. 4A): $p < 0.005$; $F(3,60) = 5.05$; $\eta p^2 = 0.20$; beta (Fig. 4D): $p < 0.05$; $F(3,60) = 3.02$; $\eta p^2 = 0.13$). Post-hoc analyses revealed that the Post measurements were lower when compared to Pre (only a trend for beta band), R1 and R2 ($p < 0.05$), indicating that improvement in cup stacking performance are related to alpha/beta power reductions in the frontal channels following cup stacking practice. No main effects of group or time *vs* group interaction was found for either alpha or beta bands.

Central channel (Cz). There was a significant main effect of time on the absolute power for the alpha and beta bands (alpha (Fig. 4B): $p < 0.001$; $F(3,60) = 5.22$; $\eta p^2 = 0.20$; beta (Fig. 4E): $p < 0.005$; $F(3,60) = 7.60$; $\eta p^2 = 0.27$). Post-hoc analyses revealed that the Post measurements were lower when compared to Pre (only a trend for the alpha and beta bands), R1 (trend for alpha) and R2 ($p < 0.05$). These results indicate that improvements in cup stacking performance are related to alpha/beta power reductions in the central channels following cup stacking practice. No main effect of group or time *vs* group interaction was found for both alpha and beta bands.

Parietal channels (CP1 and CP2). There were no significant main effects for the alpha absolute power (Fig. 4C). However, there was a significant main effect of time on the absolute power for the beta band ($p < 0.005$; $F(3,60) = 5.82$; $\eta p^2 = 0.22$, Fig. 4F). Post-hoc analyses revealed that the Post measurements were lower when compared to Pre and R1. These results indicate that the improvement in cup stacking performance is related to beta power reductions in

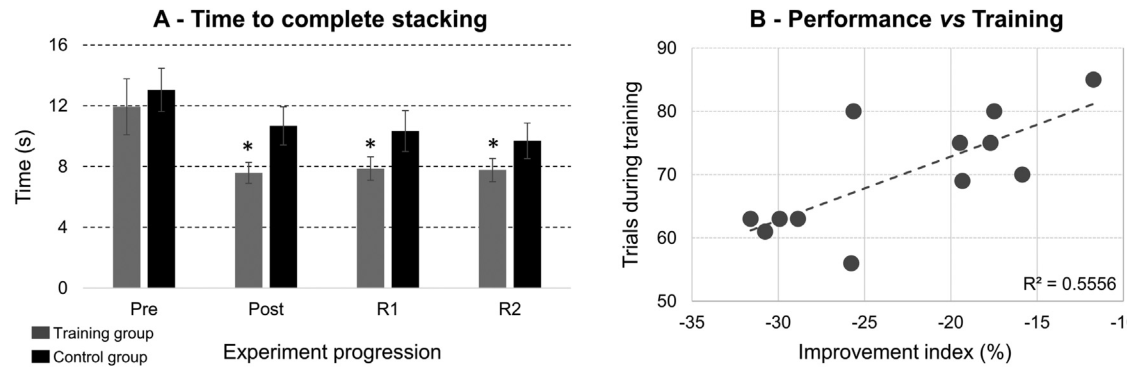

Figure 3 Panel A illustrated the mean (SD) time to complete cup stacking before (Pre) and after training (Post), as well as 24 hours (R1) and 1 week after training (R2), for the training group (gray bars) and control group (black bars). In B, Pearson correlation coefficient between performance improvement index (delta time, x axis) and number of trials performed during training (y axis). * denotes significant difference in relation to the Control group at the same time points, as well as in relation to Pre from both groups ($p < 0.005$).

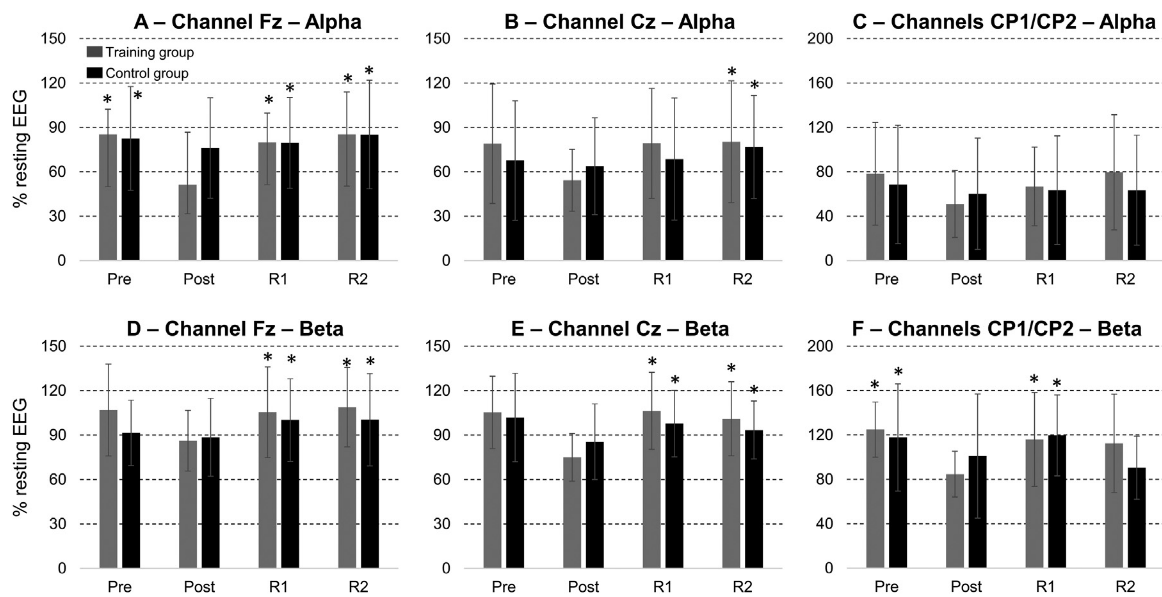

Figure 4 Mean (SD) alpha absolute power (8—12 Hz) in the A: frontal; B: central; and C: parietal areas; D: and beta absolute power (13—30 Hz) in the in the frontal; E: central and; F: parietal areas before (Pre) and after training (Post), as well as 24 hours (R1) and 1 week after training (R2), for the training group (gray bars) and control group (black bars* denotes significant difference in relation to the Pre measurement ($p < 0.05$).

the parietal channels following cup stacking practice. No main effect of group or time *vs* group interaction was found for both alpha and beta bands.

4. Discussion

The main findings of the present study were that participants from both groups improved their time to perform cup stacking, however the training group showed the largest improvements. This was accompanied by a reduction in alpha and beta power in brain areas related to motor control and somatosensory integration, as well as in the frontal area (related to motor planning and attention) from pre- to post-test for both groups. These results suggest that a minimum exposure to cup stacking (about 5 repetitions) can improve task performance and detectable changes in electrocortical activity. However, a single session of cup stacking training was not sufficient to elicit noticeable cortical adaptations from 24 hours after training.

4.1. Time to complete cup stacking

The training group presented a considerable reduction in the time to complete cup stacking from Pre- to Post-test, with no further trend to reductions in the following measurements (R1 and R2). However, the control group demonstrated a linear trend to reductions in time to complete the task from Post-test to R1, and from R1 to R2 (Fig. 3B). This result suggest that the training group retained their new motor patterns, whereas the control group kept learning with each trial. Furthermore, the first phase of acquiring a new motor skill is related to cognition, where participants would choose the optimal strategy by trial-and-error and thereby discard non-working elements [3]. Moreover, participants performing the greatest number of trials may have been faster to define an optimal strategy to perform cup stacking, allowing for substantial improvements in motor performance. It has been shown that motor history is an essential process for motor learning [32], therefore training participants undergoing greater exposure to a similar movement pattern would have advantages to fixate motor memory.

4.2. Training-related changes in the motor area

The reduced alpha and beta power on the central channels from Pre- to Post-test indicate training-related adaptations in brain areas related to motor control [28], corroborating studies describing learning adaptations in motor and sensorimotor brain areas following a learning protocol [10—12]. Likewise, Cunha (2006) and Pollok (2014) found reduction in the beta power in these same brain areas following a the learning of a bimanual typewriting task [13] and the learning of a unilateral reaction time task [14]. It is noteworthy that the previously cited studies investigated motor learning on tasks non-similar to the cup stacking proposed in the present study. Therefore, our results demonstrate the time-course changes in spectral power during a highly complex bimanual task that heavily relies on visuo-motor coordination and motor planning.

4.3. Training-related changes in the parietal area

The reduced beta power Post-test in the channels over the corroborates another study describing learning-related changes in EEG power spectrum following a typewriting task [13]. These reductions in power in the parietal area may represent the early stages of reducing the demands of somatosensory integration towards defining the actual movement strategies and speed. The cup stacking task requires attention to acceleration/deceleration and a high level of precision in landing light cups on top of each other. Therefore, the involvement of somatosensory areas is highly expected during early stages of learning, and it may be reduced with training.

4.4. Training-related changes in Frontal area

The reductions from Pre-to Post-test in the alpha and beta power at the frontal EEG channels for groups suggest that a cup stacking training volume as low as five trials was sufficient to induce changes in electrocortical activity at the frontal lobe. The frontal lobe is responsible for movement planning [33,34], potentially allowing the use of other brain areas to maximize performance [35]. Ludyga et al. (2017) investigated training-related changes in electrocortical activity following four weeks of a cognitively demanding high-cadence cycling training. The authors found reduced beta power on the frontal area of the brain, but no changes in alpha activity. The reduced alpha power in the frontal area may be related to the greater cognitive complexity during cup stacking, which demands engagement of additional neuronal circuitry to engage in the task.

In general, the absolute power was reduced immediately after the training period and returned to baseline (Pre-test) levels in R1 and R2, suggesting that the brain processing related to performing the newly acquired skill was not retained. This result is in contradiction with the improved time to complete cup stacking, as the time to complete the task during R1 and R2 was similar to Post-test. It is likely that the single training session was sufficient to induce adaptations in other non-cortical brain areas, consequently not allowing for direct measurement [36]. Training-related changes in the cerebellar cortex could explain the increase in performance, as this brain structure is associated with refinement of already existing movement patterns [8,29]. Moreover, there is involvement of other brain areas such as thalamus and putamen on the acquisition and consolidation of a motor skill [37]. Therefore, we speculate that trained participants could acquire better skills in cup stacking initially through changes in cortical and sub-cortical control, allowing the fixation of a motor pattern that subsequently became refined through cerebellar processing. In practice, our results also demonstrate that motor performance improvements in sports involving manual handling of objects present rapid improvements from low exposure to the motor task.

The lack of differences in EEG power (across all investigated brain areas) between training and control group suggests—in principle—that despite the improvement in cup stacking performance, there are no relevant changes in electrocortical activity for the training group. However, our experimental design contains four time points (Pre, Post, R1 and R2), potentially influencing the training-related outcomes from EEG data. There were significant group x time interactions in the alpha band in the central channels, and trends for significant interactions in the beta band from frontal channels ($p = 0.06$) and in the alpha band for the parietal channels ($p = 0.07$). In all cases, the absolute power in the post-test from the training group was significantly lower compared to the other conditions ($p < 0.05$), potentially demonstrating an immediate training-related change in brain activity for the training group.

The current study was limited to the use of only 14 EEG channels, substantially reducing the possibility of applying sophisticated methods to extract information from scalp EEG recordings. The use of independent component analysis has been highly relevant for unravelling neural information in mobile recording conditions when high-density EEG (>32) electrodes are used [22,38]. In this study, independent component analysis has been used for data pre-processing and cleaning [26,39]. Therefore, further studies applying high-density EEG on training protocols such as cup stacking are needed.

In summary, 20 minutes of practice was sufficient to immediately improve cup stacking performance and retain such performance levels up to seven days after the training session. Moreover, there were generalized reductions in the alpha and beta power - immediately after the training session - over the brain areas responsible for movement planning, motor control and somatosensory integration.

Disclosure of interest

The authors declare that they have no competing interest.

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