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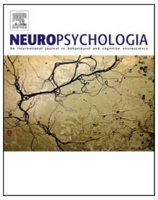

Selective cortical adaptations associated with neural efficiency in visuospatial tasks – the comparison of electroencephalographic profiles of expert and novice artists

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ABSTRACT

Visuospatial cognition encapsulates an individual's ability to efficiently navigate and make sense of the multimodal cues from their surroundings, and therefore has been linked to expert performance across multiple domains, including sports, performing arts, and highly skilled tasks, such as drawing (Morrone and Minini, 2023). As neural efficiency posits a task-specific functional reorganization facilitated by long-term training, the present study employs a visuospatial construction task as a means of investigating the neurophysiological adaptations associated with expert visuospatial cognitive performance. Electroencephalogram (EEG) data acquisitions were used to evaluate the event-related changes (ER%) and statistical topographic maps of nine expert versus nine novice artists. The expert artists displayed overall higher global ER% compared to the novices within task-active intervals. Significant increases in relative ER% were found in the theta (t (10) = 3.528, p = 0.003, CI = [27.3,120.9]), lower-alpha (t (10) = 3.751, p = 0.002, CI = [28.2,110.5]), upper-alpha (t (10) = 3.829, p = 0.002, CI = [50.2,189.8]), and low beta (t (10) = 4.342, p < 0.001, CI = [37.0,114.9]) frequency bands, when comparing the experts to the novice participants. These results were particularly found in the frontal (t (14) = 2.014, p = 0.032, CI = [7.7,245.4]) and occipital (t (14) = 2.647, p = 0.010, CI = [45.0,429.7]) regions. Further, a significant decrease in alpha ER% from lower to upper activity (t (8) = 4.475, p = 0.001, CI = [21.0, 65.8]) was found across cortical regions in the novice group. Notably, greater deviation between lower and upper-alpha activity was found across scalp locations in the novice group, compared to the experts. Overall, the findings demonstrate potential local and global EEG-based indices of selective cortical adaptations within a task requiring a high degree of visuospatial cognition, although further work is needed to replicate these findings across other domains.

1. Introduction

Visuospatial cognition is a multifaceted skillset which interconnects both the recognition and re-recognition of objects (i.e., visual), and the orientation, reorientation, and three-dimensional operation of an object (i.e., spatial; Linn and Petersen, 1985; Rilea et al., 2004). Further, visuospatial cognition may be compartmentalized into the combination of 1) visual cognition; which involves the use of both input data and existing knowledge to construct a representation of an environment, in which actions are informed upon (Cavanagh, 2011); and 2) spatial cognition; which involves the processing of multimodal information from the environment, as a means of configuring perceptual understanding and recognition of three-dimensional spatial relationships (Peng et al., 2022). By interlinking the two, visuospatial cognition combines the perception, interpretation, and utilization of local and global-based cues as a means of defining how we comprehend and interact with our environment (Chueh et al., 2017). This plays a fundamental role in a multitude of both every day and specialized activities (Possin, 2010). As a result, high degrees of visuospatial intelligence have been linked to expert performance across multiple domains, based upon an individual's ability to efficiently navigate and make sense of the multimodal cues present within their surroundings (Morrone and Minini, 2023).

Within electroencephalogram (EEG) data, the frequency of cortical oscillations depends upon interactions between neurons and interneurons, and are controlled on a local basis (Pfurtscheller & Lopes da

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Silva, 1999). As a result, neural oscillations may be subdivided into frequency bands of: delta (δ), theta (θ), alpha (α), beta (β), and gamma (γ) - all of which have been associated with different forms of cognitive processing and conscious states (Niedermeyer and Lopes da Silva, 1982). Notably, the alpha band is directly linked with the accessing and processing of information which is involved in navigating the environment (e.g., sensorimotor processing, action observation, and movement planning; Klimesch, 1997, 1999, 2012; Klimesch et al., 2007, 2011; Minarik et al., 2018; Quandt et al., 2011; Horst et al., 2013), and therefore acts as a means of evaluating brain functions during states of visuospatial processing (Klimesch, 2012; Morrone and Minini, 2023; Peylo et al., 2021).

The neuronal and intraneuronal interactions which control frequency components of EEG signals are reflected in measurable increases or decreases in relative power amplitudes, known as event-related synchronization (ERS; Pfurtscheller, 1992) and event-related desynchronization (ERD; Pfurtscheller, 1977; Pfurtscheller and Aranibar, 1977), respectively. For instance, an increase in involvement of neural networks (i.e., increase in cell assembly) is thought to result in an increase in the global distribution of ERD (Pfurtscheller & Lopes da Silva, 1999). Further, it can be said that decreases in alpha powers (i.e., ERD) are indicative of increased cortical activation, whereas increases in alpha powers (i.e., ERS) indicate a decrease in cortical recruitment (Lindsley and Wicke, 1974). Although changes in alpha activity were thought to merely reflect cell assembly, more recent interpretations involve them acting as functional correlates of inhibition and mechanisms of top-down control (Klimesch et al., 2007; Sauseng et al., 2005; Wianda and Ross, 2019). For instance, alpha band ERSs are thought to represent cortical inhibition, whereas alpha ERDs correspond to the release of inhibition (Klimesch, 2012; Pfurtscheller & Lopes da Silva, 1999)

As rhythmic alpha oscillations typically associate with sensory, motor, and cognitive information processing (Klimesch, 2012; Pfurtscheller & Lopes da Silva, 1999), spatially selective cortical activations within the alpha band have been identified to have a functional role in efficient neuronal processing (Womelsdorf and Fries, 2007). Noting the inverse relationship alpha power has with regional cortical activation (Lindsley and Wicke, 1974), decreases in activation (thus, ERS or less ERD) have been associated with better task performance, whereas increases in activation have been related to poorer task performance (Doppelmayr et al., 2005; Neubauer and Fink, 2009; Smith et al., 1999).

Subsequently, the inverse relationship between alpha activity and performance has been established within participants of various domain-specific tasks, such as in chess players (Grabner et al., 2006), elite athletes (Babiloni et al., 2010a,b; Del Percio et al., 2008a, 2009, 2011; Guo et al., 2017a,b; Milton et al., 2007; Peng et al., 2022), experts in aiming and shooting professions (Haufler et al., 2000; Loze et al., 2001; Zhang et al., 2021), and in formal piano training (Krings et al., 2000). As a result, such findings are in support of the idea of ‘neural efficiency’ (Haier et al., 1988; Haier et al., 1992a).

“Neural efficiency” hypothesis posits that long-term training experienced by experts results in reduced neural activity (Del Percio et al., 2009; Guo et al., 2017a), whereby experts are more neuronally effective, and thereby require less cerebral cortical resources in order to execute a task for which the expert is familiar. For instance, extensive practice in athletes has been linked to ‘neural efficiency’, stemming from the development of task-related efficient organization of neural networks (Babiloni et al., 2010a; Del Percio et al., 2008b). Although this functional reorganization has been speculated to be task-specific (Guo et al., 2017a), neural efficiency have also been identified in various forms neural processing, such as word fluency (Cnudde et al., 2021; Parks et al., 1988), memory (Charlot et al., 1992; Grabner et al., 2004; Ruff et al., 2003; Rypma et al., 2002, 2005; Rypma and D’Esposito, 1999), spatial skills (Guo et al., 2017a; Haier et al., 1988; Haier et al., 1992b), and overall intelligence (Colom et al., 2010; Grabner et al., 2004, 2006; Haier et al., 2004; Neubauer et al., 1995; Neubauer et al., 2005; Neubauer and Fink, 2009).

Due to the emphasized task-specific nature of neural efficiency, the present study appoints experts within the visuospatial construction task of objective drawing, as a means of investigating the neural efficiency hypothesis within visuospatial tasks. This is done to provide insight on the neurophysiological manner in which high degrees of visuospatial cognition may be indexed. Notably, the present study administers a visuospatial task that is familiar to the expert subjects, meaning that the experts did not require an element of learning to perform the task. Additionally, as the current literature pertaining to visuospatial performance is predominantly evaluated within athletic populations, the present study investigates visuospatial performance beyond this demographic, in order to broaden the specification of EEG-based neuronal adaptions associated with high degrees of visuospatial cognition.

To our knowledge, no studies have quantified the neural adaptations associated with heightened visuospatial-based performance, using expert artists. Within the present study, interpretation of the neural substrate associated with expert visuospatial processing involved evaluating global neural differences between expert and novice participants during a task-active interval, of the visuospatial construction task of objective drawing. Drawing is a multifaceted skillset, which requires a complex network of functional organization as a means of constructing and transforming internal representations of multimodal information (Marusic et al., 2021). Through transforming visual information and internal perception into fine hand movements (La Femina et al., 2009; McCrea, 2014), drawing acts as a comprehensive psychomotor task which involves key forms of processing, such as eye-hand coordination, visuospatial processing, and other higher-order cognitive functions (Marusic et al., 2021). Further, drawing is a high-order cognitive ability which utilizes external cues (i.e., multimodal stimuli from the surrounding) with internally derived representations (i.e., pertaining to memory or imagery processes; Yuan and Brown, 2015; Griffith and Bingman, 2020). Importantly, the fundamental constituents of drawing can be said to involve the encoding of visuospatial information, paired with related sensorimotor processes (e.g., execution of sensory-guided movements; McCrea, 2014). As a result, drawing acts as a powerful tool to assess neuropsychological constituents of visuospatial processing, therefore was used in the present study in order to investigate the task-specific neural adaptations associated with visuospatial cognition.

As the argument of neural efficiency predominantly pertains to alpha band activity, the present study sought to examine this band. Overall, the present study addresses the following primary aims: 1) to evaluate the neural differences in expert vs novice participants, in alignment with the ‘neural efficiency’ hypothesis, 2) to evaluate how event-related percentage (ER%) exhibition varies within the lower (8–10Hz range) vs upper (10–12 Hz range) alpha band across groups, and 3) to identify any dominant patterns of source location and/or lateralization. Based upon previous research, the following was hypothesized: 1) an increase in alpha ER% would be found in the expert participants, in alignment with the ‘neural efficiency’ hypothesis, 2) compared to the lower-alpha band, upper-alpha band activity would more sensitive to tasks requiring high degrees of visuospatial cognition, for its association with both visuospatial cognition and expert performance as a whole, and 3) distinct patterns of parieto-occipital alpha activity may be found across the groups, in alignment with the relative attentional demands of the task. As a secondary aim, other frequency bands were also examined, as a means of identifying potential alternative neuronal adaptations associated with increased visuospatial performance, beyond the alpha band.

2. Methods

Participants. EEG data acquisitions of eighteen right-handed participants, including nine novice artists (mean age = 26.78 ± 5.43 years, n = 3 female, 6 male) and nine expert artists (mean age = 29.88 ± 4.91 years, n = 4 female, 5 male), were investigated. Expert participants were defined as having at least 10 years of experience building up their visual art skillset, as well as practicing their expertise vocationally on regular basis. The visual art skillset encompassed drawing, painting, and tattooing. At the time of the study, the experts actively produced visual art forms regularly and/or worked in the art industry (i.e., as commissioned artists). Novices were defined as individuals who neither actively engage in the creation of visual arts, nor have ever received any formal training in the domain. Ethical approval was granted by the St Mary's University Ethics Committee, in accordance with the ethical standards established in the Declaration of Helsinki. Informed written consent was received by all participants, whereby information was outlined on how the study would be conducted, the right to withdraw from the study at any time, and how the results would be used.

Materials. EEG data were collected at 512 samples per second (sps), using a NEURO PRAX® TMS-EEG system (Eldith, NeuroCare Group, Ilmenau, Germany) system, providing full band quantitative neurofeedback. The system used concentric-ring Ag/AgCl electrodes powered by a NeuroConn Magestim Eldith (Eldith, NeuroCare Group, Ilmenau, Germany) device, along with a with a 27-electrode cap, following the international 10:20 system. A separate ground electrode was placed on the lateral forehead region. The electrode sites were aggregated into the following regions: Frontal (FP1, FP2, Fz), Central (Fc1, Fc2, C3, C4, Cz), Parietal (A1, A2, P3, P4, Pz), Occipital (O1, O2), Left Temporal (F3, F7, Fc5, T3, Cp5, T5), and Right Temporal (F4, F8, Fc6, T4, Cp6, T6), as displayed in Fig. 1. Homologous hemispheric electrode sites were segmented into the left (FP$_1$, F$_3$, F$_7$, Fc$_1$, Fc$_5$, C$_3$, Cp$_5$, A$_1$, T$_3$, T$_5$, P$_3$, O$_1$) and the right (FP$_2$, F$_4$, F$_8$, Fc$_2$, Fc$_6$, C$_4$, Cp$_6$, A$_1$, T$_4$, T$_6$, P$_4$, O$_1$) hemispheres.

All data were pre-processed and analyzed using EEGLAB 2021.2 (Delorme and Makeig, 2004) within MATLAB_R2021a (TheMathWorks, Inc., Natick, Massachusetts, U.S.A.). Topographical maps were achieved through the topographical mapping neuro-visualizing software available in EEGLAB (MATLAB Toolbox, California, USA), using the default colour map.

For the visuospatial task, participants were provided with a single sheet of A4 paper, a selection of graphite pencils, and an eraser. As the familiarity of input stimuli (i.e., reference objects) plays a dominant role in the recruitment of neural substrate associated with drawing (i.e., objective drawing vs non-objective drawing; Griffith and Bingman, 2020; Raimo et al., 2021; Yuan and Brown, 2015), the present study used objects which were familiar to the participants, in order to elude the recruitment of mechanisms associated with creative processing. The reference objects existed in the form of a group of three artificial apples; synthetic apples were used in order to ensure consistency throughout the experiment and for each participant. In addition to the physical setup, reference printout images of the exact layout were provided, and placed on the left side of the paper being drawn on. Participants were free to exam the real objects prior to the drawing task but were asked to draw using the printout images as reference, once the drawing task started. The image printouts were used to minimize muscular movements (i.e., unnecessary head turns, eye movements, etc.), that may impact the acquisitions of electrical data.

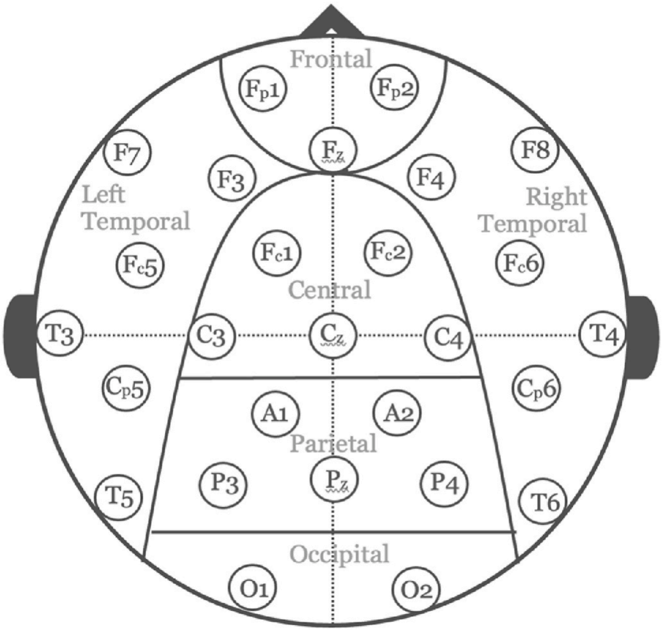

Fig. 1. The electrode placement used, based upon the International 10–20 system. The electrodes were segmented into the following regions: Frontal, Central, Parietal, Occipital, and Left and Right Temporal.

Procedure. Participants entered a sensory-controlled environment, which contained minimal electronic noise. The electrode cap was then fitted to the participant, with each electrode attached after scalp preparation. Prior to data collections, electrode impedance was monitored and ensured to be kept $<5\text{k}\Omega$. Once EEG recordings commenced, participants followed a discrete task protocol of 1-min eyes open, whereby participants were asked to look straight ahead in a relaxed state; and 10 min drawing (see Fig. 2). Continuous EEG data were collected throughout the 10-min drawing interval. The 1-min eyes open resting procedure was performed to serve as an intraparticipant baseline for EEG data to be normalized against. Buffer times of 3 s were used before and after each task, in order to account for edge artifacts.

Participants were instructed to realistically draw a reference photo of a set of apples, as accurately as possible, within a 10-min interval. No direct instructions on *how* to draw the apples, were provided. Participants were instructed to continuously engage with the task and to use all 10 min, if possible. The participants were also informed prior to the task that the state of the final drawing was not going to be assessed. Such instructions were to ensure that the participants put less emphasis on the end result, and more focused on the active task of replicating the reference objects. All participants used the entire 10-min allocated task time. Prior to the task, participants were also given the instruction to limit unnecessary muscular movements (i.e., head turns and eye movement), as much as comfortably possible to preserve the quality of the EEG signal.

EEG data processing. Cleaning and pre-processing procedures were based upon the open source standardized computational EEG toolbox (Delorme and Makeig, 2004), created by the software architect of EEGLAB. Pre-processing of EEG data involved down sampling data from 512 Hz to 128 Hz, the removal of edge artifacts, applying a low-pass notch filter (cut-off frequency of 50Hz) and a high-pass filter (cut-off frequency of 0.5Hz), and cleaning through the CleanLine plugin in EEGLAB. Re-sampling of data was performed to increase processing time and filters were applied to remove line-noise and to minimize low drifts.

Independent Component Analysis (ICA) was conducted in order to identify and remove unwanted activity. This was achieved through both filtering and rejecting components which were predicted to account for non-brain activity equal to or above 90%, and through visual inspection-based artifact rejection analysis (Delorme and Makeig, 2004). ICA components which were removed included oculomotor artifact and visual contextual complexes (such as eye-blinks and eye-movements), muscular activities, and other non-brain related complexes (Jung et al., 2000).

Data analysis. Power spectrum analysis was performed, whereby each data set was processed through Fast Fourier Transform using Welch's Method with windows of 500 sampling points and 375 sampling point overlaps. Power Spectrum Densities (PSD) values were decomposed into a total of eight divided bands, which were defined as the following: delta (1–3 Hz), theta (4–7 Hz), low alpha (8–10 Hz), high alpha (10–12 Hz), low beta (13–16 Hz), high beta (17–30 Hz), low gamma (31–45Hz), and high gamma (55–70 Hz). The EEG data was log$_{10}$ transformed to achieve higher degrees of normal distribution, therefore interpretations of individual frequency bands should be

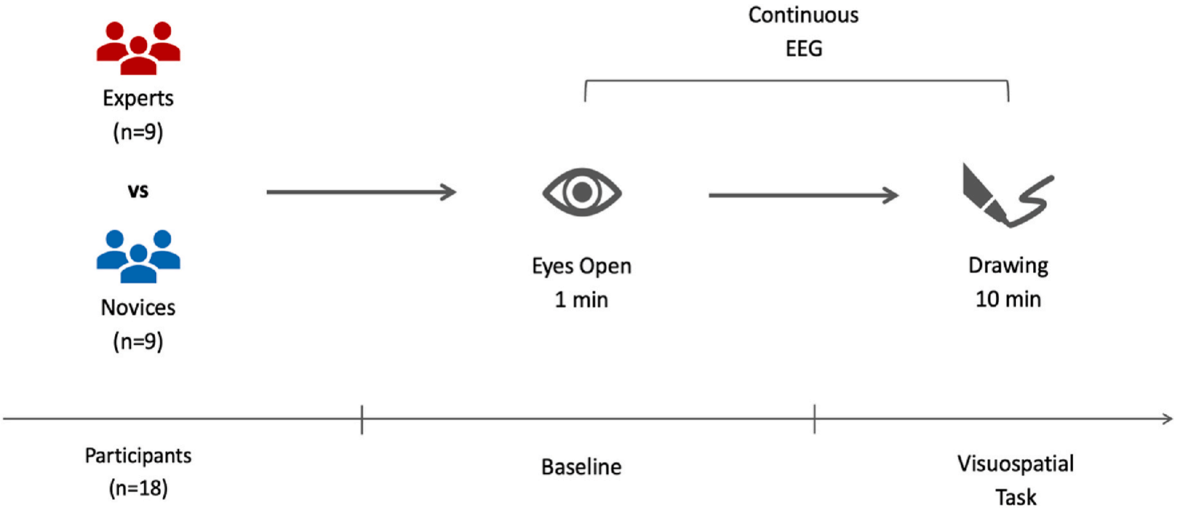

Fig. 2. Timeline of the experimental design.

considered on respective scales. Frequency band event-related changes were quantified as the percentage changes in frequency specific PSD values of active task intervals (i.e., drawing task compared to the baseline (i.e., waking-rest) condition; Pfurtscheller et al., 1997; Pfurtscheller and Aranibar, 1979; Pfurtscheller and Neuper, 1994). Negative values (i.e., event-related desynchronizations; ERD) represent decreases in power of the task interval from the baseline interval, and positive values (i.e., event-related synchronizations; ERS) represent increases in relative powers. Event-related percentages (ER%) were calculated according to the formula:

$$\frac{Task - Baseline}{Baseline} * 100$$

As an outcome of the formula, with powers reflecting regional neural oscillatory synchrony, negative percentage values may indicate cortical activation in the form of ERD, and positive values are representative of cortical deactivation (i.e., ERS; Pfurtscheller, 2003; Womelsdorf and Fries, 2007).

Topographical map evaluation. Projected planar positions of the hemispheric scalp models were evaluated through statistical topographical maps using EEGLAB. The EEGLAB robust statistical topographical map comparisons evaluated the difference between group (expert vs novice) power spectrum density scalp distribution, for each frequency band. Additionally, visual inspection-based analysis was conducted, based upon these topographical maps.

Statistical evaluation. Statistical analysis was performed using SPSS version 29.0.0.0 (SPSS, Inc, Armonk, NY, USA). Kolmogorov–Smirnov tests were conducted and evaluated to test the normality of the distribution of the data (Weiss, 1989). The relationship between the upper and lower-alpha band was initially investigated using paired samples *t*-tests, comparing upper and lower ER% values across each region, for the groups independently. Such evaluation resulted in two t-tests: one *t*-test for each group, with regional division of electrode sites resulted in 6 data points for each *t*-test. Interactions were followed up with two independent three-factorial ANOVA's. Such ANOVA's used average ER % values to 1) compare upper and lower-alpha band values for expertise, and cortical regions, and 2) compare upper and lower-alpha band values for each expertise and across each hemisphere, as a means of evaluating any potential dominant patterns of hemispheric laterality. The first ANOVA was subjected to two (alpha frequency band segments: upper vs lower) x two (group: experts vs. novices) x six (regions: frontal, central, parietal, occipital, and left and right temporal). The second ANOVA was subjected to two (alpha frequency band segments: upper vs lower) x two (group: experts vs. novices) x two (hemisphere: left vs. right homologous sites). Post hoc comparisons were performed using Bonferroni corrected t-tests, to follow up significant effects. The criterion alpha level was set to 0.05.

To compare the differences in task-related cortical activity between groups across all frequency bands, regional analysis resulted in performing independent samples *t*-tests, which compared differences in regional ER% between groups. Such evaluation resulted in 8 *t*-tests: one *t*-test for each frequency band, with the regional division of electrode sites resulting in 6 data points for each *t*-test. Electrode site regional investigation was also performed, whereby *t*-tests compared novice and expert ER% values across all frequency bands for each electrode region. Such evaluation resulted in 6 *t*-tests: one for each cortical region, with 8 data points per test, one for each frequency band. Statistical evaluation was adapted from previous research (Benedek et al., 2011; Haufler et al., 2000; Magosso et al., 2019; Manor et al., 2023).

3. Results

Alpha band. Within the initial investigation, a significant decrease in alpha ER% from lower to upper activity ($t\ (8) = 4.475$, $p = 0.001$, CI = [21.0, 65.8]) was observed across cortical regions within the novice group. The expert group did not display any significant difference in relative ER% ($p > 0.05$) between subdivisions of the alpha band. Within the follow up investigation, although significant effects were found for expertise in the regional (F (23,108) = 10.650, $p = 0.002$) and hemispheric (F (5,96) = 8.190, $p = 0.005$) evaluations, no further statistical interactions were identified ($p > 0.05$).

Although the novice group exhibited greater global mean difference (MD) between the upper and lower-alpha bands (MD = 43.4 ± 29.1 %) compared to the experts (MD = 0.1 ± 1.9 %), the experts showed greater coefficients of variation (CV) between the two bands (CV% = 1900%), compared to the novices (CV% = 67.1%). As presented in Fig. 3, the expert group displayed globally homogenous alpha activity across both sub-bands, wherein consistent alpha ERS% was found across both bands across all cortical regions.

The experts displayed strongest ERS% in the occipital lobe, and weakest in the parietal lobe. Further, with novices displaying predominantly ERD% within both upper and lower-alpha bands, strongest ERD % was found in the upper-alpha band of right and left temporal regions (respectively). The novices also exhibited greatest difference between lower and upper-alpha band within the central region and temporal lobes (both left and right; as displayed in Fig. 3c), with ERD% being strongest in the upper-alpha band across all regions. The difference between alpha sub-bands was found to be the least in the frontal and parietal lobes within the novice group, with ERS% being found in frontal

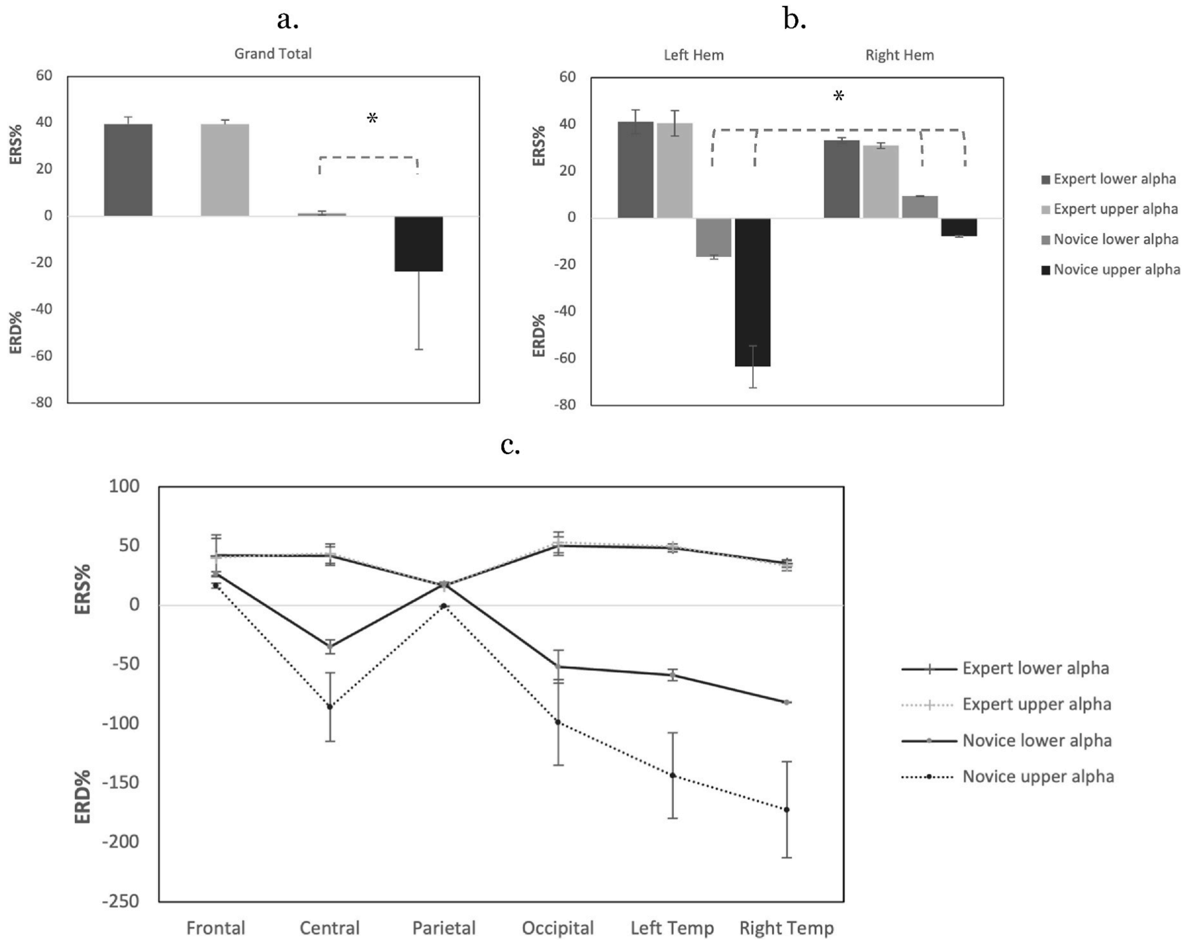

Fig. 3. Displays the event-related percentage (ER%) power changes, comparing the groups (expert vs novice) for the lower and upper-alpha bands. The graphs are segmented into the following: a) global ER% evaluation, b) right and left hemispheric ER% evaluation, c) regional ER% evaluation. Increases in ER% indicate event-related synchronizations (ERS) relative to baseline, where decreased values indicate event-related desynchronizations (ERD). Error bars represent one standard deviation. * Significant difference, $p < 0.05$.

and parietal regions.

Hemispheric evaluation was also conducted (Fig. 3b), as a means of identifying any patterns of alpha-based laterality. Although the expert group exhibited similar lower and upper-alpha activity across both hemispheres, greater ERS% was found in the left hemisphere. As for the novices, greatest difference between the alpha bands was found in the left hemisphere, with the strongest ERD% being exhibited in the upper band of the left hemisphere.

Overall global frequency distribution. Relative to baseline conditions, task-related ER% changes were compared across groups for each frequency band. Expert participants displayed relative increases in ER% from baseline conditions across all frequency bands, except for the delta band, whereby experts displayed a decrease in ER%. Further, novice participants displayed ERD across all bands apart from the theta, lower-alpha, and low beta band. For each frequency band, *t*-tests were conducted to compare mean differences of relative ER% across all cortical regions for the visuospatial construction task. Significant increases in relative ER% occurred for the theta ($t\ (10) = 3.528$, $p = 0.003$, CI = [27.3,120.9]), lower-alpha ($t\ (10) = 3.751$, $p = 0.002$, CI = [28.2,110.5]), upper-alpha ($t\ (10) = 3.829$, $p = 0.002$, CI = [50.2,189.8]), low beta ($t\ (10) = 4.342$, $p < 0.001$, CI = [37.0,114.9]) frequency bands, when comparing the experts to the novice participants.

Regional investigation. Task-related PSD changes were also compared across groups for each cortical region (as segmented and described above). For each electrode site region, *t*-tests were conducted to compare mean differences of relative ER% across all frequency bands for the task. Although experts displayed heightened relative ER% values across nearly all electrode regions, significant increases in relative ER% were particularly displayed in the frontal ($t\ (14) = 2.014$, $p = 0.032$, CI = [7.7,245.4]) and occipital ($t\ (14) = 2.647$, $p = 0.010$, CI = [45.0,429.7]) regions across all frequency bands, when comparing the experts to the novice participants.

Topographical maps. Normalized parametric statistics topographical maps were used to evaluate neuronal activity across all electrode sites, comparing the experts and novices during task-active intervals. As displayed in Fig. 4, across all frequency bands, evident ERS was displayed in prefrontal electrode sites (Fp1 and Fp2) of the expert, while Fz predominantly displayed evident ERD, compared to the novice. ERS was also displayed across nearly all frequency bands for within the experts within right temporal regions (Fc6 and T4) and central regions (Fc2 and C4). Further, statistical difference was also in found in the left temporal lobe on electrode site Cp5, and Pz (parietal lobe), which both indicated increased spectral values in the experts compared to the novices on these sites. Another notable electrode cite was T3, representing differences in activity in the left temporal regions.

4. Discussion

The primary aim of this study was to evaluate the neural correspondences associated with a visuospatial construction task, comparing the neural substrate of expert and novice artists. As selective cortical adaptions, such as that hypothesized by 'neural efficiency', posits task-

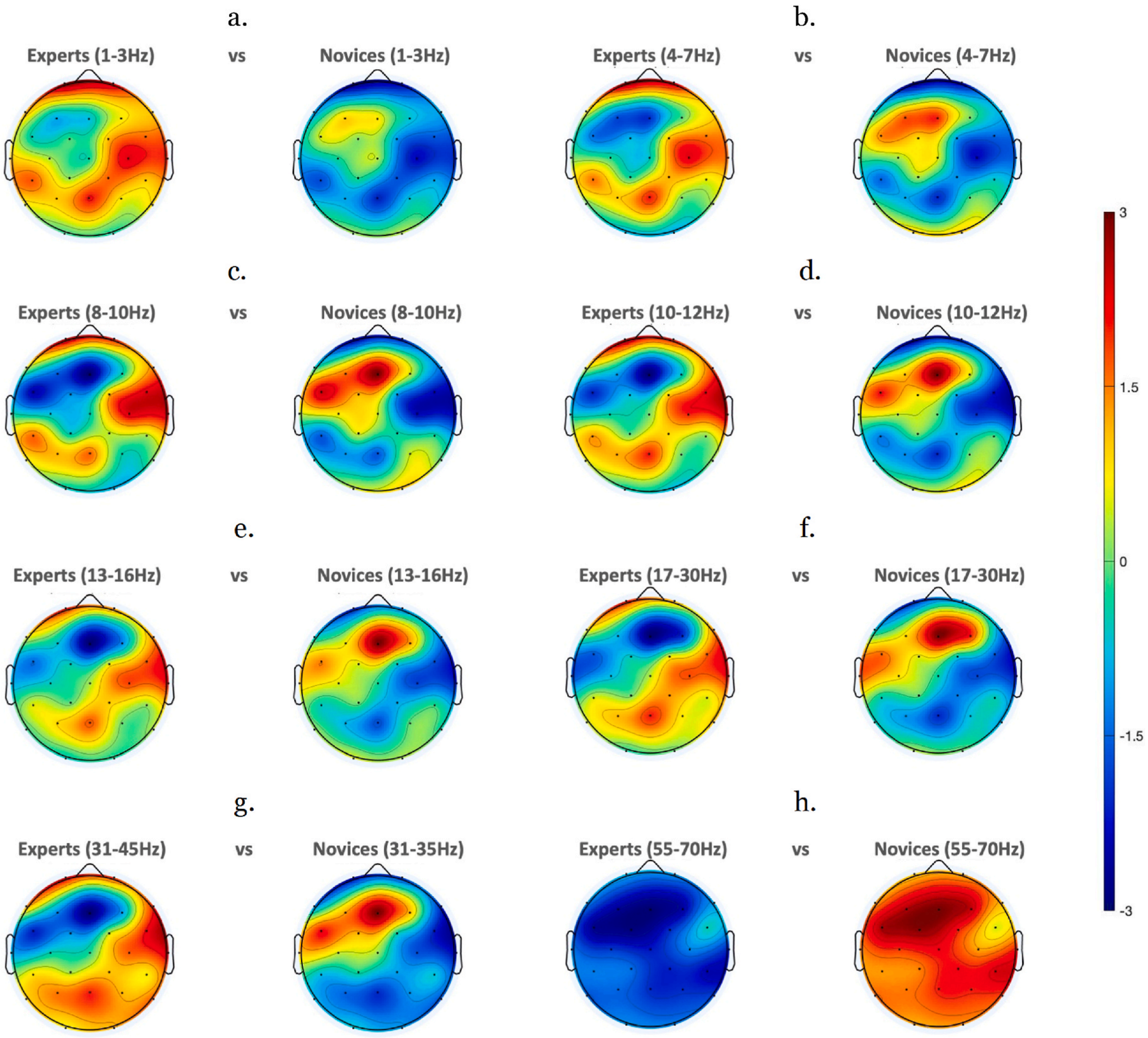

Fig. 4. The statistical topographical plots display the normalized interindividual parametric differences in Power Spectrum Densities (μV^2/Hz) between the groups (experts vs novices, respectively per each panel), across all electrode sites. These topographical plots were computed for each frequency band segment: a) delta (1–3 Hz), b) theta (4–7 Hz), c) low alpha (8–10 Hz), d) high alpha (10–12 Hz), e) low beta (13–16 Hz), f) high beta (17–30 Hz), g) low gamma (31–45Hz), and h) high gamma (55–70 Hz). Within the normalized statistical comparisons, parametric statistics of magnitudes 3, 2, and 1, equate to $p = 0.001$, 0.01, and 0.1, respectively, with positive values indicating relative increases in powers (i.e., event-related synchronizations; ERS; as represented in red), and blue indicating relative deceases (i.e., event-related desynchronizations; ERD).

specific functional reorganization facilitated by long-term training, the present study employed a visuospatial construction task in the form of drawing, in order to investigate such adaptations for visuospatial cognition. Due to how the argument of neural efficiency predominantly pertains to alpha band activity, the present study sought to primarily examine this band. Although, all frequency bands were briefly examined as a means of identifying potential alternative neuronal adaptation associated with increased visuospatial performance. As a result, this study aimed to provide insight on both the local and global task-specific selective cortical adaptations related to visuospatial cognition, with application across other expert performance domains.

Overview of EEG activity in the visuospatial construction task. Widespread cortical activity was indexed by task-related percentage changes (ER%), as well as normalized parametric statistics topographical map evaluation, comparing expert and novice artist during task-active intervals. The findings revealed overall increased global frequency powers in the experts compared to the novice participants, across nearly all frequency bands. With lower frequency band powers (such as the theta and alpha bands) being inversely related to cortical activation (Haufler et al., 2000), increases in relative powers within such bands, can be said to be representative of decreased cortical activation. As significant increases in theta, alpha (lower and upper), and beta (low) ER% were found when comparing the experts to the novice artists, these findings may therefore indicate a decrease in cortical activation within the theta and alpha band. Such results suggest a net reduced role of cortical processing required by the experts during the visuospatial task, particularly specified by lower frequency band activity. Since decreases in activation (thus, ERS or less ERD) have been associated with better task performance, and increases in activation have been related to poorer task performance (e.g., Babiloni et al., 2008; Haufler et al., 2000; Kerick et al., 2004; Wang et al., 2020; Zhang et al., 2021), the present study supports the literature which shows greater widespread cortical synchrony being displayed within experts compared to novices.

As fewer cortical neurons are activated during task performance as a result of a more developed skillset, practice-related increases in lower frequency bands (i.e., the alpha band) suggests an inverse relationship between ERD detection and performance (Smith et al., 1999). This means that training can be thought to facilitate the development of task-related efficient organization of neural networks. Therefore, the present results suggest that frequency bands such as the alpha, theta, and low beta may act as potential neuronal markers of the cortical adaptations associated with training of visuospatial task performance. Interestingly, superior visuomotor performance has also been displayed in expert athletes in the form of globally lower cortical activity, which acted as an index for spatially selective cortical processes (i.e., neural efficiency; Del Percio et al., 2009). This may be explained by the way in which globally distributed cortical adaptions are thought to reflect the development of an internal model or procedural memory, particularly due to how such forms of processing involve the integration of widespread subprocesses and cortical regions (e.g., visual, motor, executive processes, etc.; Beek, 2000; Kerick et al., 2004; Kinsbourne, 1982). This means that the global adaptations described in the present findings may reflect increased stability in corresponding neuronal networks, associating with an increased state of automaticity during the task performance. Such an idea supports the assumption of selective activation of cortical populations during visuospatial performance in experts, in alignment with the neural efficiency hypothesis (Del Percio et al., 2009). For this reason, the results of the present study are in support of the literature suggesting that global adaptations are associated with neural efficiency within the domain of visuospatial processing.

Although the expert artists displayed overall higher global ER% compared to the novice participants during the task-active interval, an alternative interpretation must be considered. Importantly, such findings may be indicative of the reallocation of neuronal resources to necessary and relevant processing units, rather than an overall decrease in activity. For instance, decreased cortical activation has been found in brain regions which are irrelevant to task execution, and therefore are proposed to be involved in the inhibition of cognitive functions that are not directly related to the execution of the task being performance (both in cognitive and motor tasks; Klimesch et al., 2007; Pfurtscheller, 1992). As an example, selective inhibition of task-irrelevant cortical regions was found to be concurrent with greater activation in task-relevant regions during golf puts, which acted to support the manifestation of psychomotor efficiency with training (Gallicchio et al., 2017). For this reason, the psychomotor efficiency hypothesis suggests the enhancement in cognitive-motor processing, characterized by the suppression of task-irrelevant preparatory processes (Cohen, 2016; Hatfield, 2018; Hatfield and Hillman, 2001; Morrone and Pedlar, 2024).

Due to the volume conduction properties of EEG, measured signals detect surface activity of cortical structures, making the detection and localization of subcortical sources difficult (DiFrancesco et al., 2008). Therefore, decreases in global cortical activity may not represent a net decrease in cortical resource usage, but rather the reallocation of resources away from irrelevant networks to more relevant brain circuitry for the task at hand (such as subcortical networks; e.g., Alperin et al., 2005; Falkmer and Gregersen, 2005; Gilchriest, 2015). In conclusion, although the experts within present study displayed greater widespread cortical synchrony in alignment with neural efficiency hypothesis, such activity may reflect the reallocation of resources away from surface cortical structures rather than a net decrease in energy requirement. For this reason, further research employing a combination of neuroimaging techniques (such as the combination of EEG and functional magnetic resonance imaging (fMRI)), is suggested in order to locate and characterize spatially selective neural indices found in EEG measurements.

Alpha band evaluation. Widespread cortical alpha oscillations are modulated by thalamo-cortical and cortico-cortical interaction (Lopes da Silva, 1991), which both facilitate and inhibit the transmission of sensorimotor and cognitive information within the brain (Brunia, 1999; Deeny et al., 2003; Pfurtscheller & Lopes da Silva, 1999; Steriade and Llinás, 1988). Therefore, alpha oscillations are related to sensorimotor processing, visuospatial attention, cognitive and memory performance, action observation, and movement planning (Klimesch, 1997, 1999, 2012; Klimesch et al., 2007, 2011; Minarik et al., 2018; Quandt et al., 2011; Horst et al., 2013). Since the selective engagement of thalamo-cortical and cortico-cortical loops may facilitate the modulation of alpha activity for optimal visuomotor performance (Del Percio et al., 2009), the alpha band was used as a salient marker for visuospatial cognitive performance within the present study.

In alignment with the ‘neural efficiency’ hypothesis, decreased alpha activity was found in the expert participants, compared to the novice group. Specifically, significant relative increases in global ER% were displayed for both lower-alpha and upper-alpha when comparing the experts to the novices. These results are commensurate with previous results in tasks requiring high degrees visuospatial intelligence. For instance, elite athletic performance has been associated with global decreased alpha ERD, found both in the lower (8–10Hz) and higher alpha (10–12Hz) (Del Percio et al., 2009). This suggests that visuo-motor performance directly corresponds to global decreases in cortical activation (e.g., in expert athletes; Del Percio et al., 2009). Therefore, it has been hypothesized that elite performance may be characterized by a reduction in ERD compared to non-athletes during visuo-motor tasks related to the domain of specialty (Jann et al., 2009), and in experts compared to novice in aiming/preparation tasks (Haufler et al., 2000).

Interestingly, alpha ERD has been found to be associated with engaging in cognitive tasks (Başar et al., 2001; Klimesch et al., 1993; Mazaheri, 2010), such as mental arithmetic (Boiten et al., 1992; Grabner and De Smedt, 2011), language translation (Grabner et al., 2007), and visuo-verbal judgment (Pfurtscheller and Klimesch, 1992). As alpha activity is associated with information processing and automatic motor control (Klimesch, 2012; Klostermann et al., 2007; Pollok et al., 2009; Zhuang et al., 1997), subsequent changes in alpha activity may reflect differences in attention-based demands and resource allocation. For this reason, global alpha ERD being displayed by the novices in the present study, is suggested to reflect an increase of intentional engagement and attention associated with the task, due to a lack to automatic motor control.

It has also been shown that an increase in alpha power is accompanied by tasks requiring mental imagery and imagination, whereby a reduction in alpha power occurs in response external stimuli as compared to internal mental processing (Cooper et al., 2003, 2006). In further support, alpha synchronizations occur during the performance of various cognitive tasks (e.g. memory, attention, etc.), whereby a decrease in cortical activity (i.e., ERS or quantifiably less ERD) has been suggested to occur as a result of skill acquisition (Busch and Herrmann, 2003; Cooper et al., 2003; Herrmann et al., 2004; Jensen, 2002; Klimesch et al., 1999, 2000). The present expert group displayed alpha ERS, which may indicate that the experts' process involves greater reliance on internal strategies of self-instructions during task execution (Abernethy and Russell, 1987; Harris and Harris, 1984; Singer et al., 1993).

Further, differential reactivity of oscillations may be found within the subdivision of the alpha bands during a cognitive task (Bazanova and Vernon, 2014; Petsche et al., 1997), such that the specificity of cortical response to task-related demands is achieved by decomposing the alpha band into its lower (low alpha; 8–10 Hz) and upper (high alpha; 11–13 Hz) constituents. Lower-alpha activity is reflected in non-specific attention and anticipatory processes (“expectancy”), and is said to act as a global generalization for the cognitive processing of arousal (Haufler et al., 2000; Kerick et al., 2001; Klimesch, 1999; Pfurtscheller & Lopes da Silva, 1999; Smith et al., 1999). As lower-alpha activity attenuates over global scalp locations, it is said to be more widespread distributed, due to the inverse relationship the frequency power has with the active neuronal density in the cortex. This is due to how large active neuronal density (i.e., large populations of cortical neurons) distribute across widespread anatomical regions, contributing to the activity detected during task-active intervals (Pfurtscheller, 1988). As a result, upper-alpha band activity is localized to regional activations, thus often act in topographically restricted domains (Klimesch, 2012; Schneider and Shiffrin, 1977).

Upper-alpha activity modulates in alignment with task-specific attentional processes, and is thereby said to activate in accordance with task-specific attention demands (Gevins, 1997; Klimesch et al., 1990; Pfurtscheller and Klimesch, 1992). Interestingly, evidence suggests that upper-alpha activity is sensitive to variations to prior experience with observed actions (Hummel et al., 2002; Marshall et al., 2009), indicating that mechanisms of visuomotor-related processing may particularly be accompanied by changes in upper-alpha oscillatory activity in the brain. Consequentially, lower-alpha band oscillation is said to reflect neural systems involved in global attentive readiness, while upper-alpha rhythms facilitate task-related oscillation towards the transmission of sensorimotor or semantic information (Klimesch, 1996, 1999; Klimesch et al., 1998). As a result, it may be said that modulation in the of alpha rhythms might support both global attention-based (i.e., lower-alpha activity) and localized task-specific processes (i.e., upper-alpha activity; Klimesch, 1996, 1999; Klimesch et al., 1998).

It was hypothesized that compared to the lower-alpha band, upper-alpha band activity would be more sensitive to tasks requiring high degrees of visuospatial cognition, for its association both with visuospatial cognition (Morrone and Minini, 2023) and expert performance as a whole (Grabner et al., 2004). Event-related percentage (ER%) variations were investigated, comparing lower (8–10Hz range) vs upper (10–12 Hz range) alpha activity within each group. The novice group exhibited a significant decrease in alpha ER% from lower to upper activity across all cortical regions, whereas the expert group did not. Further, the novices predominantly displayed relative lower and upper-alpha ERD%, where the experts displayed widespread relative lower and upper-alpha ERS%. These results are in alignment with widespread lower-alpha ERD reflecting foundational attention and arousal processes, which act in response to most task demands (Fink, 2005; Fink and Neubauer, 2004; Grabner et al., 2007; Klimesch et al., 1998). This indicates that the novices had greater active conscious contribution to the task at hand.

Conversely, the experts displayed lower-alpha ERS, which is interpreted as a potential representation of an increase in attention-based automaticity by the experts, compared to the novices. Although upper-alpha ERD tend to be topographically restricted to task-relevant regions (Klimesch et al., 1993, 1997), in a general sense, this activity is linked to the access, search, and use of semantic information from long-term memory (Klimesch et al., 1998). As the novice group displayed upper-alpha ERD, these results are interpreted as a potential display of active attempts to retrieve a skillset to perform the task. Such interpretation is supported by research showing stronger upper-alpha ERD corresponded with high memory performance (Doppelmayr et al., 2005; Klimesch et al., 1997), meaning that a possible active and conscious retrieval of psychomotor memory-based processing is present in the novices, in an attempt to perform the task to the best of their ability. As a result, as upper-alpha ERD reflects task-specific requirement (Klimesch et al., 1993, 1997), the present results are interpreted as the correspondence of attention and memory-based domains, required by the novices to perform the visuospatial construction task.

Additionally, high deviation between the lower and upper-alpha band was displayed in the novice group across cortical regions, whereas the expert group displayed globally similar alpha activity across both sub-bands (as found in Fig. 3). In the context of the neural processing representations of each subdivision of the alpha band, such results indicate that the visuospatial expert process may involve a cohesion between attentive readiness (i.e., lower-alpha oscillations), and task-specific attentional demands (i.e., upper-alpha band). This may once again act as a representation of a state of automaticity during the task. Further, increased upper-alpha power has been associated with the suppression of learnt motor processing mechanisms (particularly in sensorimotor; Hummel et al., 2002). Therefore, it is speculated that inducing practice within the novice group may elicit an increase in upper-alpha power, thereby decreasing the difference between the sub-bands (similar to the homogeneity of alpha band activity found within the expert group). For this reason, is hypothesized from these results, that a decrease in variation between the two alpha bands may act as a neural index for progression towards increased visuospatial performance, as induced by practice. Although further evidence to support such claim is required.

Regional ER%. EEG activity can be localized to distinct cortical areas, and therefore can be made sense of in alignment with the functioning of the region in which it is detected. In other words, source localization acts to support the characterization of local frequency band distribution. For instance, sleep spindle alpha-oscillations originate from the thalamus, the mu-rhythm (8–12 Hz) motor functions derive from the central sulcus, and visual alpha EEG in perceptual functions is said to derive from occipital lobes (Gonçalves et al., 2006). Furthermore, in a traditional sense, occipital alpha activity is said to reflect externally derived visual attention, where increases in alpha power of the occipital region reflect decreased in visual attention demands (Könönen and Partanen, 1993; Vijn et al., 1991). Interlinkingly, visuospatial orientation processes are mediated by a pragmatic dorsal pathway, which terminates in the parietal cortex (Jeannerod et al., 1995). As a result, smaller alpha power (i.e., stronger ERD or less ERS) over occipital-parietal regions of the brain are associated with increased visual processing, and is generally suggestive of an attentive (versus relaxed wakefulness) brain state (Mo et al., 2013). Consequentially, this suggests that activity both of the occipital and parietal cortex, may be of interest for the differentiation of expertise within the visuospatial constructions task in the present study. For this reason, the last hypothesis entailed distinguishable patterns of parieto-occipital alpha activity existing across the groups, in alignment with the relative attentional demands of the task. This was particularity due to the association parieto-occipital activity has with visuospatial processing (Magosso et al., 2019).

As a means of identifying dominant patterns of source location and/or lateralization*,* task-related PSD changes were compared across groups for each cortical region. Although the experts within the present study displayed heightened relative ER% values across nearly all electrode sites, significant increases in relative ER% were particularly displayed in the frontal and occipital regions across all frequency bands, when comparing the experts to the novice participants. Due to occipital ERS being strong in the experts within the alpha band, such results indicate that the experts experienced a relative decreased reliability of externally derived attention, compared to their task-inactive interval. Interestingly, alpha activity within the parietal regions of the experts and novices were similar in relative ER% compared to one another, suggesting that changes in activity in such regions may not be responsible for task-related performance increases in visuospatial cognitive abilities. Although the expert did not display any distinct parietal activity compared to baseline conditions, the relatively low occipital activation (i.e., high ERS%) displayed within the experts may further be suggestive of the experts entering a state of greater reliance on internal self-instructions strategies during the task in which they are familiar with (Abernethy and Russell, 1987; Harris and Harris, 1984; Singer et al., 1993).

In extension, the idea of "neural efficiency" within athletic populations has been known to exist during visuospatial tasks, whereby long-term training has been found to results in the development of a more efficient task-related organization of neural networks during such tasks (Guo et al., 2017b). Although there is an emphasized task-specific element to such functional reorganization (Morrone and Pedlar, 2024), this form of associated neural efficiency has particularly been found in precision sports, such as within shooting professions. For instance, professionals in riffle shooting have shown occipital alpha power to increase during the period preceding shooting, compared to amateurs (Haufler et al., 2000; Janelle et al., 2000). During pistol shooting, increased alpha power in occipital regions was also found during the phases preceding the best shots, which was interestingly found to decrease during the phases preceding the worst shots (Loze et al., 2001). Further, expert marksmen have displayed patterns of decreased cortical activation compared to novice in aiming/preparation period, with differences found in central-temporal-parietal areas (Haufler et al., 2000). These findings indicate that with increased performance, a decrease in cortical contribution is associated with the task execution. Such reorganization can be though to be induced as effective strategies and skills are developed, which result in a decreased reliance on mechanisms of externally derived visual attention (Smith et al., 1999). For this reason, in alignment with the findings of the present study, a plausible link between increased alpha power (i.e., ERS) over occipital regions may exist to support an increase in visuospatial cognitive abilities across multiple domains.

Interestingly, alpha ERS presented in the left temporal lobes is said to reflect inhibition of explicit working memory, as well as a reduction in task-irrelevant processing (Kerick et al., 2004). Within the present study, differential activity was found in the left temporal regions, such that the experts displayed relative ERS. An interpretation of left temporal ERS being displayed by experts, is a reduction of analytical and verbal processes due to entering a state of automaticity (e.g., during aiming sport; Haufler et al., 2000). This interpretation supports the idea of functional differences in the right and left temporal areas (Lind et al., 1999), and the cortical idling hypothesis (Pfurtscheller et al., 1996). For this reason, the results of the present experts are consistent with a memory explanation of the visuospatial task. Further, object recognition, interpretation, and reconstruction are processed through the semantic ventral pathway, which terminates in the temporal lobes (Jeannerod et al., 1995). In conjunction, the pragmatic dorsal and semantic ventral pathways and regions of termination are said to be responsible for the cortical control of movement (Kerick et al., 2004). Therefore, increased alpha powers in left temporal regions are thought reflect functional coordination between such cortical regions and pathways. As a result, the increase in left temporal alpha power found in the expert, may be suggestive of how the practice endured by the experts (i.e., to achieve the skill acquisition) is thought to decrease the reliance of cortical processing associated with motor-based working memory.

Topographical maps. Normalized parametric statistics topographical maps were also used to evaluate neuronal activity across all electrode sites, comparing the expert and novice during a task-active interval. Reiterated, the psychomotor efficiency hypothesis posits an enhancement in cognitive-motor processing, characterized by the suppression of task-irrelevant preparatory processes (Hatfield, 2018; Hatfield and Hillman, 2001; Morrone and Pedlar, 2024). The magnitude of alpha ERS is said to represent the inhibition of task-irrelevant cortical regions, reflecting the suppression of irrelevant information processing (Babiloni et al., 1999; Bazanova and Vernon, 2014; Mazaheri, 2010). Therefore, decreased alpha powers reflects the release of inhibition, and thus, the cortical activation of task-relevant information processing (Neuper et al., 2006; Pfurtscheller & Lopes da Silva, 1999). Importantly, task-related practice can be thought to refine the orchestration of the neuromotor processes in the brain (Hatfield, 2018; Hatfield and Hillman, 2001). For instance, practice is thought to induce a decrease in movement-specific conscious processing accompanied by increased performance, as per the theory of motor skill learning (Fitts, 1967). Therefore, the reduction in neuromotor noise, or decreased alpha activity (i.e., increased power) is thought to occur in alignment with movement planning and preparation processes as performance, due to a task becoming more automatic with practice (Smith et al., 1999). Although some research suggests that no such link between conscious processing and training exists (Malhotra et al., 2015), overall, psychomotor practice is thought to support an enhancement in task execution and performance, whereby suppressions in task-irrelevant processes (i.e., diverting resources away from less relevant cortical regions) allows the reallocation of resources to task-relevant regions (Hatfield, 2018; Hatfield and Hillman, 2001; Morrone and Pedlar, 2024).

In comparing the present experts to the novices, evident ERS was displayed in prefrontal electrode sites (Fp1 and Fp2) of the experts, although Fz predominantly displayed evident ERD. ERS was also displayed for the experts within right temporal regions (Fc6 and T4). Interestingly, activity in the right temporal region is associated with the reliance of visuospatial processing during task execution (Kerick et al., 2004). More specifically, increases in alpha power on electrode site T4 have been said to indicate less effortful reliance of visuospatial processing, which may represent increased stability as visuospatial skill acquisition proceeds to higher degrees of expertise (Kerick et al., 2004). With the experts within the present study displaying ERS in right temporal regions (Fc6 and T4) compared to the novices, such findings are once again suggestive of increased automaticity experienced by the experts, within the visuospatial task. Furthermore, with ERS being displayed by the experts within central regions (Fc2 and C4), such results are suggestive of a decrease in no-go responses associated unsuitable motor-based actions (Delarosa et al., 2020). As the diminishing of alpha power over central region (i.e., over somatomotor cortex) is mediated by both real and imagined movement, as well as by proprioception (Mulholland, 1995; Pfurtscheller et al., 1994), the novices displaying relative ERD in these regions suggests an increased reliance on conscious motor-based processing. Of further note, regions which did not display any relative increases or decreases in power, may suggest that these regions are not mediated by the task-related neuronal changes modulated by practice within visuospatial construction tasks.

Based on the activity patterns found in the present study, a plausible conclusion of the experts displaying predominant ERS compared to the novices, may be that the more skilled individuals in the task, were more efficient negotiating the specific visuospatial challenges for which they are highly practiced in. This idea is consistent with findings using an aiming task as a means of characterizing visuospatial processing mechanisms, whereby increased alpha power (10–11 Hz) was found in left central, temporal, and parietal regions of the experts compared to the novices (Haufler et al., 2000). As an extension, long-term training has been associated with more efficient visuospatial cognitive processing, for instance in the athletic population (Peng et al., 2022). Within this previous research, right hemispheric power (particularly, amplitude of electrode site P3) was significantly greater in table tennis athletes than in the control group. Such research demonstrates a right-hemisphere advantage in spatial cognition, whereby it was concluded that long-term training strengthened the visual–spatial processing ability of the athletes. As a result, the previous research concluded the visuospatial advantage effect to be reflected in the neuroplasticity of the right hemisphere (due to it being the dominant hemisphere for spatial processing), although the characteristics of laterality in non-athletes remains unclear (Peng et al., 2022). As the present study did not find any dominant patterns of laterality, it is concluded that further research to investigate the prevalence of dominant right-hemispheric advantage within experts of alternative visuospatial tasks, is warranted.

Applications and limitations. The results of the present work are proposed to assist EEG-based neurofeedback techniques and agendas associated with visuospatial cognitive performance (Morrone and Minini, 2023). For instance, such measurable quantifications of selective cortical adaptations may be used to monitor neuronal indices associated task performance, e.g., as an objective quantification along/throughout phases of skill acquisition and/or performance optimization (see: Gong et al., 2021). Although further studies using the presented EEG-based indices for the use of neurofeedback for the development and/or enhancement of visuospatial cognitive performance, is required.

While the present study suggests potential global *and* local neural correlates associated with expert visuospatial processing, several factors may have acted to improve the study, that may be of interest for future work. For instance, as mentioned, future studies may find value in pairing the EEG with other neuroimaging techniques in order to locate and characterize spatially selective neural indices found in EEG measurements. This is particularly because of the volume conduction properties of EEG measurements make localization of EEG sources difficult (DiFrancesco et al., 2008). It should also be noted that the study would have benefitted from having a larger sample size. Also, due to the cross-sectional design of the study, the causal relationship of the findings requires further investigation.

In addition, the present study predominantly emphasized the alpha band, therefore future work investigating other frequency bands in greater depth, as well as ratios between frequency bands (e.g., alpha/theta), may be of value. Further, the present study employed Welch's method, which computed Fast Fourier Transform on a shifting temporal window. For this reason, more sophisticated processing, such as the wavelet method (Murata, 2005), may be of value within future work. Lastly, value may be found in the skill acquisition of the visuospatial construction task in order to map the neural adaptations associated with selective functional reorganization within the task of objective drawing, in future work.

5. Conclusion

The present study investigated the neural substrate associated with expert visuospatial processing, through evaluating global neural differences between expert and novice participants during task-active intervals. Due to the emphasized task-specific nature of selective functional reorganization posited by neural efficiency (i.e., associated with psychomotor training; Guo et al., 2017a), experts within the visuospatial task (i.e., visual artists) were used as a means of evaluating the neural correspondences associated expertise within tasks requiring high degrees of visuospatial cognition. The expert artists displayed overall higher global ER% compared to the novice participants within the task-active interval, particularly in the theta, alpha, and beta bands. These findings were most evidently displayed in the frontal and occipital regions of the subject groups. The present results were in support of the literature which shows greater widespread cortical synchrony being displayed within experts compared to novices within various domains (such as sports), as well as with 'neural efficiency' within visuospatial cognitive tasks.

As the argument of neural efficiency predominantly pertains to alpha band activity, the alpha band was segmented and evaluated into its lower and upper band constituents. A significant decrease in alpha ER% from lower to upper activity was found across cortical regions of the novice group. Notably, greater deviation between lower and upper-alpha activity was found across scalp regions in the novice group, compared to the expert. For this reason, the results of the present study suggested global cortical adaptations in the form of differential alpha-band activity, being associated with neural efficiency within the domain of visuospatial processing. Overall, the findings of the present study demonstrated both global and local EEG-based measurable indices for selective cortical adaptations associated with performance, within tasks requiring high degrees of visuospatial cognition. As a result, the study supports a narrative of generalized neuronal adaptations associated with visuospatial construction tasks, as means of providing insight on expert performance within other domains involving high degrees of visuospatial demand, such as in sports. Further research is required in order to support this.

CRediT authorship contribution statement

Jazmin M. Morrone: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Charles R. Pedlar:** Conceptualization, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

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References

Abernethy, B., Russell, D.G., 1987. Expert-novice differences in an applied selective attention task. J. Sport Psychol. 9 (4), 326–345. https://doi.org/10.1123/jsp.9.4.326.

Alperin, N., Lee, S.H., Sivaramakrishnan, A., Hushek, S.G., 2005. Quantifying the effect of Posture on Intracranial Physiology in Humans by MRI flow studies. J. Magn. Reson. Imaging 22, 591–596. https://doi.org/10.1002/jmri.20427.

Babiloni, C., Carducci, F., Cincotti, F., Rossini, P.M., Neuper, C., Pfurtscheller, G., Babiloni, F., 1999. Human movement-related potentials vs desynchronization of EEG alpha rhythm: a high-resolution EEG study. Neuroimage 10 (6), 658–665. https://doi.org/10.1006/NIMG.1999.0504.

Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., Crespi, G., Dassù, F., Pirritano, M., Gallamini, M., Eusebi, F., 2008. Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. J. Physiol. 586 (1), 131–139. https://doi.org/10.1113/jphysiol.2007.141630.

Babiloni, C., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., Buffo, P., Cibelli, G., Soricelli, A., Eusebi, F., Del Percio, C., 2010a. Resting state cortical rhythms in athletes: a high-resolution EEG study. Brain Res. Bull. 81 (1), 149–156. https://doi.org/10.1016/j.brainresbull.2009.10.014.

Babiloni, C., Marzano, N., Infarinato, F., Iacoboni, M., Rizza, G., Aschieri, P., Cibelli, G., Soricelli, A., Eusebi, F., Del Percio, C., 2010b. "Neural efficiency" of experts' brain during judgment of actions: a high-resolution EEG study in elite and amateur karate athletes. Behav. Brain Res. 207 (2), 466–475. https://doi.org/10.1016/j.bbr.2009.10.034.

Başar, E., Başar-Eroglu, C., Karakaş, S., Schürmann, M., 2001. Gamma, alpha, delta, and theta oscillations govern cognitive processes. Int. J. Psychophysiol. 39 (2–3), 241–248. https://doi.org/10.1016/S0167-8760(00)00145-8.

Bazanova, O.M., Vernon, D., 2014. Interpreting EEG alpha activity. Neurosci. Biobehav. Rev. 44, 94–110. https://doi.org/10.1016/J.NEUBIOREV.2013.05.007.

Beek, P.J., 2000. Toward a theory of implicit learning in the perceptual-motor domain. Int. J. Sport Psychol. 31 (4), 547–554.

Benedek, M., Bergner, S., Könen, T., Fink, A., Neubauer, A.C., 2011. EEG alpha synchronization is related to top-down processing in convergent and divergent thinking. Neuropsychologia 49 (12), 3505–3511. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2011.09.004.

Boiten, F., Sergeant, J., Geuze, R., 1992. Event-related desynchronization: the effects of energetic and computational demands. Electroencephalogr. Clin. Neurophysiol. 82 (4), 302–309. https://doi.org/10.1016/0013-4694(92)90110-4.

Brunia, C.H.M., 1999. Neural aspects of anticipatory behavior. Acta Psychol. 101 (2–3), 213–242. https://doi.org/10.1016/S0001-6918(99)00006-2.

Busch, N.A., Herrmann, C.S., 2003. Object-load and feature-load modulate EEG in a short-term memory task. Neuroreport 14 (13), 1721–1724. https://doi.org/10.1097/00001756-200309150-00013.

Cavanagh, P., 2011. Visual cognition. Vis. Res. 51 (13), 1538–1551. https://doi.org/10.1016/j.visres.2011.01.015.

Charlot, V., Tzourio, N., Zilbovicius, M., Mazoyer, B., Denis, M., 1992. Different mental imagery abilities result in different regional cerebral blood flow activation patterns during cognitive tasks. Neuropsychologia 30 (6), 565–580. https://doi.org/10.1016/0028-3932(92)90059-U.

Chueh, T.-Y., Huang, C.-J., Hsieh, S.-S., Chen, K.-F., Chang, Y.-K., Hung, T.-M., 2017. Sports training enhances visuo-spatial cognition regardless of open-closed typology. PeerJ 5, e3336. https://doi.org/10.7717/peerj.3336.

Cnudde, K., Van Hees, S., Brown, S., Van Der Wijk, G., Pexman, P.M., Protzner, A.B., 2021. Increased Neural Efficiency in Visual Word Recognition: Evidence from Alterations in Event-Related Potentials and Multiscale Entropy. https://doi.org/10.3390/e23030304.

Cohen, R.A., 2016. The Neuropsychology of Attention (Critical Issues in Neuropsychology), second ed. Springer.

Colom, R., Karama, S., Jung, R.E., Haier, R.J., 2010. Human intelligence and brain networks. Dialogues Clin. Neurosci. 12 (4), 489–501. https://doi.org/10.31887/DCNS.2010.12.4/rcolom.

Cooper, N.R., Croft, R.J., Dominey, S.J.J., Burgess, A.P., Gruzelier, J.H., 2003. Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses. Int. J. Psychophysiol. 47 (1), 65–74. https://doi.org/10.1016/S0167-8760(02)00107-1.

Cooper, N.R., Burgess, A.P., Croft, R.J., Gruzelier, J.H., 2006. Investigating evoked and induced electroencephalogram activity in task-related alpha power increases during an internally directed attention task. Neuroreport 17 (2), 205–208. https://doi.org/10.1097/01.wnr.0000198433.29389.54.

Deeny, S.P., Hillman, C.H., Janelle, C.M., Hatfield, B.D., 2003. Cortico-cortical Communication and superior performance in skilled marksmen: an EEG coherence analysis. J. Sport Exerc. Psychol. 25 (2), 188–204. https://doi.org/10.1123/jsep.25.2.188.

Del Percio, C., Rossini, P.M., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., Lino, A., Fiore, A., Toran, G., Babiloni, C., Eusebi, F., 2008a. Is there a "neural efficiency" in athletes? A high-resolution EEG study. Neuroimage 42 (4), 1544–1553. https://doi.org/10.1016/j.neuroimage.2008.05.061.

Del Percio, C., Rossini, P.M., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., Lino, A., Fiore, A., Toran, G., Babiloni, C., Eusebi, F., 2008b. Is there a "neural efficiency" in athletes? A high-resolution EEG study. Neuroimage 42 (4), 1544–1553. https://doi.org/10.1016/J.NEUROIMAGE.2008.05.061.

Del Percio, C., Babiloni, C., Bertollo, M., Marzano, N., Iacoboni, M., Infarinato, F., Lizio, R., Stocchi, M., Robazza, C., Cibelli, G., Comani, S., Eusebi, F., 2009. Visuo-attentional and sensorimotor alpha rhythms are related to visuo-motor performance in athletes. Hum. Brain Mapp. 30 (11), 3527–3540. https://doi.org/10.1002/hbm.20776.

Del Percio, C., Infarinato, F., Marzano, N., Iacoboni, M., Aschieri, P., Lizio, R., Soricelli, A., Limatola, C., Rossini, P.M., Babiloni, C., 2011. Reactivity of alpha rhythms to eyes opening is lower in athletes than non-athletes: a high-resolution EEG study. Int. J. Psychophysiol. 82 (3), 240–247. https://doi.org/10.1016/j.ijpsycho.2011.09.005.

Delarosa, B.L., Spence, J.S., Motes, M.A., Wing To, Vanneste, S., Kraut, M.A., Hart, J., 2020. Identification of Selection and Inhibition Components in a Go/NoGo Task from EEG Spectra Using a Machine Learning Classifier. https://doi.org/10.1002/brb3.1902.

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 (1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

DiFrancesco, M.W., Holland, S.K., Szaflarski, J.P., 2008. Simultaneous EEG/functional magnetic resonance imaging at 4 tesla: correlates of brain activity to spontaneous alpha rhythm during relaxation. J. Clin. Neurophysiol. 25 (5), 255–264. https://doi.org/10.1097/WNP.0b013e3181879d56.

Doppelmayr, M., Klimesch, W., Hödlmoser, K., Sauseng, P., Gruber, W., 2005. Intelligence related upper alpha desynchronization in a semantic memory task. Brain Res. Bull. 66 (2), 171–177. https://doi.org/10.1016/J.BRAINRESBULL.2005.04.007.

Falkmer, T., Gregersen, N.P., 2005. A comparison of eye movement behavior of inexperienced and experienced drivers in real traffic environments. Optom. Vis. Sci. 82 (8), 732–739. https://doi.org/10.1097/01.opx.0000175560.45715.5b.

Fink, A., 2005. Event-related desynchronization in the EEG during emotional and cognitive information processing: differential effects of extraversion. Biol. Psychol. 70 (3), 152–160. https://doi.org/10.1016/j.biopsycho.2005.01.013.

Fink, A., Neubauer, A.C., 2004. Extraversion and cortical activation: effects of task complexity. Pers. Indiv. Differ. 36 (2), 333–347. https://doi.org/10.1016/S0191-8869(03)00100-4.

Fitts, P.M., 1967. Human Performance. Brooks.

Gallicchio, G., Cooke, A., Ring, C., 2017. Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. Sport, Exercise, and Performance Psychology 6 (1), 89–102. https://doi.org/10.1037/spy0000077.

Gevins, A., 1997. High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice. Cerebr. Cortex 7 (4), 374–385. https://doi.org/10.1093/cercor/7.4.374.

Gilchriest, J.A., 2015. Visual search optimization as a quantitative measurement of cognitive efficiency. Functional Neurology, Rehabilitation, and Ergonomics 5 (1).

Gonçalves, S.I., De Munck, J.C., Pouwels, P.J.W., Schoonhoven, R., Kuijer, J.P.A., Maurits, N.M., Hoogduin, J.M., Van Someren, E.J.W., Heethaar, R.M., Lopes Da Silva, F.H., 2006. Correlating the alpha rhythm to BOLD using simultaneous EEG/fMRI: inter-subject variability. Neuroimage 30 (1), 203–213. https://doi.org/10.1016/J.NEUROIMAGE.2005.09.062.

Grabner, R.H., De Smedt, B., 2011. Neurophysiological evidence for the validity of verbal strategy reports in mental arithmetic. Biol. Psychol. 87 (1), 128–136. https://doi.org/10.1016/J.BIOPSYCHO.2011.02.019.

Grabner, R.H., Fink, A., Stipacek, A., Neuper, C., Neubauer, A.C., 2004. Intelligence and working memory systems: evidence of neural efficiency in alpha band ERD. Cognit. Brain Res. 20 (2), 212–225. https://doi.org/10.1016/J.COGBRAINRES.2004.02.010.

Grabner, R.H., Neubauer, A.C., Stern, E., 2006. Superior performance and neural efficiency: the impact of intelligence and expertise. Brain Res. Bull. 69 (4), 422–439. https://doi.org/10.1016/j.brainresbull.2006.02.009.

Gong, A., Gu, F., Nan, W., Qu, Y., Jiang, C., Fu, Y., 2021. A Review of Neurofeedback Training for Improving Sport Performance From the Perspective of User Experience. Frontiers in Neuroscience 15. https://doi.org/10.3389/fnins.2021.638369.

Grabner, R.H., Brunner, C., Leeb, R., Neuper, C., Pfurtscheller, G., 2007. Event-related EEG theta and alpha band oscillatory responses during language translation. Brain Res. Bull. 72 (1), 57–65. https://doi.org/10.1016/J.BRAINRESBULL.2007.01.001.

Griffith, F.J., Bingman, V.P., 2020. Drawing on the brain: an ALE meta-analysis of functional brain activation during drawing. Arts Psychother. 71, 101690 https://doi.org/10.1016/J.AIP.2020.101690.

Guo, Z., Li, A., Yu, L., 2017a. "Neural efficiency" of athletes' brain during visuo-spatial task: an fMRI study on table tennis players. Frontiers in Behavioral Neuroscience 11. https://doi.org/10.3389/fnbeh.2017.00072.

Guo, Z., Li, A., Yu, L., Ann Barker, L., Reynolds, D., Prpic, V., 2017b. 'Neural Efficiency'" of Athletes' Brain During Visuo-Spatial Task: an fMRI Study On Table Tennis Players. https://doi.org/10.3389/fnbeh.2017.00072.

Haier, R.J., Siegel, B.V., Nuechterlein, K.H., Hazlett, E., Wu, J.C., Paek, J., Browning, H. L., Buchsbaum, M.S., 1988. Cortical glucose metabolic rate correlates of abstract reasoning and attention studied with positron emission tomography. Intelligence 12 (2), 199–217. https://doi.org/10.1016/0160-2896(88)90016-5.

Haier, R.J., Siegel, B., Tang, C., Abel, L., Buchsbaum, M.S., 1992a. Intelligence and changes in regional cerebral glucose metabolic rate following learning. Intelligence 16 (3–4), 415–426. https://doi.org/10.1016/0160-2896(92)90018-M.

Haier, R.J., Siegel, B.V., MacLachlan, A., Soderling, E., Lottenberg, S., Buchsbaum, M.S., 1992b. Regional glucose metabolic changes after learning a complex visuospatial/motor task: a positron emission tomographic study. Brain Res. 570 (1–2), 134–143. https://doi.org/10.1016/0006-8993(92)90573-R.

Haier, R.J., Jung, R.E., Yeo, R.A., Head, K., Alkire, M.T., 2004. Structural brain variation and general intelligence. Neuroimage 23 (1), 425–433. https://doi.org/10.1016/J.NEUROIMAGE.2004.04.025.

Harris, Dorothy V., Harris, Bette L., 1984. The Athlete's Guide to Sports Psychology : Mental Skills for Physical People. Leisure Press.

Hatfield, B.D., 2018. Brain dynamics and motor behavior: a case for efficiency and refinement for superior performance. Kinesiol. Rev. 7 (1), 42–50. https://doi.org/10.1123/kr.2017-0056.

Hatfield, B.D., Hillman, C.H., 2001. The psychophysiology of sport: a mechanistic understanding of the psychology of superior performance. Handbook of Sport Psychology 2, 362–386.

Haufler, A.J., Spalding, T.W., Santa Maria, D.L., Hatfield, B.D., 2000. Neuro-cognitive activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and novice shooters. Biol. Psychol. 53 (2–3), 131–160. https://doi.org/10.1016/S0301-0511(00)00047-8.

Herrmann, C.S., Senkowski, D., Röttger, S., 2004. Phase-Locking and amplitude modulations of EEG alpha. Exp. Psychol. 51 (4), 311–318. https://doi.org/10.1027/1618-3169.51.4.311.

Horst, A.C., van Lier, R., Steenbergen, B., 2013. Mental rotation strategies reflected in event-related (de)synchronization of alpha and mu power. Psychophysiology 50 (9), 858–863. https://doi.org/10.1111/psyp.12076.

Hummel, F., Andres, F., Èller, E.A., Dichgans, J., Gerloff, C., 2002. Inhibitory Control of Acquired Motor Programmes in the Human Brain.

Janelle, C.M., Hillman, C.H., Apparies, R.J., Murray, N.P., Meili, L., Fallon, E.A., Hatfield, B.D., 2000. Expertise differences in cortical activation and gaze behavior during rifle shooting. J. Sport Exerc. Psychol. 22 (2), 167–182. https://doi.org/10.1123/jsep.22.2.167.

Jann, K., Dierks, T., Boesch, C., Kottlow, M., Strik, W., Koenig, T., 2009. BOLD correlates of EEG alpha phase-locking and the fMRI default mode network. Neuroimage 45 (3), 903–916. https://doi.org/10.1016/J.NEUROIMAGE.2009.01.001.

Jeannerod, M., Arbib, M.A., Rizzolatti, G., Sakata, H., 1995. Grasping objects: the cortical mechanisms of visuomotor transformation. Trends Neurosci. 18 (7), 314–320.

Jensen, O., 2002. Oscillations in the alpha band (9-12 Hz) increase with memory load during retention in a short-term memory task. Cerebr. Cortex 12 (8), 877–882. https://doi.org/10.1093/cercor/12.8.877.

Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., McKeown, M.J., Iragui, V., Sejnowski, T.J., 2000. Removing electroencephalographic artifacts by blind source separation. Psychophysiology 37 (2), 163–178. https://doi.org/10.1111/1469-8986.3720163.

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. https://doi.org/10.1016/S0301-0511(01)00116-8.

Kerick, S.E., Douglass, L.W., Hatfield, B.D., 2004. Cerebral cortical adaptations associated with visuomotor practice. Med. Sci. Sports Exerc. 36 (1), 118–129. https://doi.org/10.1249/01.MSS.0000106176.31784.D4.

Kinsbourne, M., 1982. Hemispheric specialization and the growth of human understanding. Am. Psychol. 37 (4), 411–420. https://doi.org/10.1037/0003-066X.37.4.411.

Klimesch, W., 1996. Memory processes, brain oscillations and EEG synchronization. Int. J. Psychophysiol. 24 (1–2), 61–100. https://doi.org/10.1016/S0167-8760(96)00057-8.

Klimesch, W., 1997. EEG-alpha rhythms and memory processes. Int. J. Psychophysiol. 26 (1–3), 319–340. https://doi.org/10.1016/S0167-8760(97)00773-3.

Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res. Rev. 29 (2–3), 169–195. https://doi.org/10.1016/S0165-0173(98)00056-3.

Klimesch, W., 2012. Alpha-band oscillations, attention, and controlled access to stored information. Trends Cognit. Sci. 16 (12), 606–617. https://doi.org/10.1016/j.tics.2012.10.007.

Klimesch, W., Pfurtscheller, G., Mohl, W., Schimke, H., 1990. Event-related desynchronization, ERD-mapping and hemispheric differences for words and numbers. Int. J. Psychophysiol. 8 (3), 297–308. https://doi.org/10.1016/0167-8760(90)90020-E.

Klimesch, W., Schimke, H., Pfurtscheller, G., 1993. Alpha frequency, cognitive load and memory performance. Brain Topogr. 5 (3), 241–251. https://doi.org/10.1007/BF01128991.

Klimesch, W., Doppelmayr, M., Pachinger, T., Ripper, B., 1997. Brain oscillations and human memory: EEG correlates in the upper alpha and theta band. Neurosci. Lett. 238 (1–2), 9–12. https://doi.org/10.1016/S0304-3940(97)00771-4.

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., Schwaiger, J., 1998. Induced alpha band power changes in the human EEG and attention. Neurosci. Lett. 244 (2), 73–76. https://doi.org/10.1016/S0304-3940(98)00122-0.

Klimesch, W., Doppelmayr, M., Schwaiger, J., Auinger, P., Winkler, T., 1999. `Paradoxical' alpha synchronization in a memory task. Cognit. Brain Res. 7 (4), 493–501. https://doi.org/10.1016/S0926-6410(98)00056-1.

Klimesch, W., Doppelmayr, M., Röhm, D., Pöllhuber, D., Stadler, W., 2000. Simultaneous desynchronization and synchronization of different alpha responses in the human electroencephalograph: a neglected paradox? Neurosci. Lett. 284 (1–2), 97–100. https://doi.org/10.1016/S0304-3940(00)00985-X.

Klimesch, W., Sauseng, P., Hanslmayr, S., 2007. EEG alpha oscillations: the inhibition–timing hypothesis. Brain Res. Rev. 53 (1), 63–88. https://doi.org/10.1016/j.brainresrev.2006.06.003.

Klimesch, W., Fellinger, R., Freunberger, R., 2011. Alpha oscillations and early stages of visual encoding. Front. Psychol. 2 https://doi.org/10.3389/fpsyg.2011.00118.

Klostermann, F., Nikulin, V.V., Kühn, A.A., Marzinzik, F., Wahl, M., Pogosyan, A., Kupsch, A., Schneider, G.-H., Brown, P., Curio, G., 2007. Task-related differential dynamics of EEG alpha- and beta-band synchronization in cortico-basal motor structures. Eur. J. Neurosci. 25 (5), 1604–1615. https://doi.org/10.1111/j.1460-9568.2007.05417.x.

Könönen, M., Partanen, J.V., 1993. Blocking of EEG alpha activity during visual performance in healthy adults. A quantitative study. Electroencephalogr. Clin. Neurophysiol. 87 (3), 164–166. https://doi.org/10.1016/0013-4694(93)90122-C.

Krings, T., Töpper, R., Foltys, H., Erberich, S., Sparing, R., Willmes, K., Thron, A., 2000. Cortical activation patterns during complex motor tasks in piano players and control subjects. A functional magnetic resonance imaging study. Neurosci. Lett. 278 (3), 189–193. https://doi.org/10.1016/S0304-3940(99)00930-1.

La Femina, F., Paolo Senese, V., Grossi, D., Venuti, P., 2009. The Clinical Neuropsychologist A Battery for the Assessment of Visuo-Spatial Abilities Involved in Drawing Tasks. https://doi.org/10.1080/13854040802572426.

Lind, J.C., Flor-Henry, P., Koles, Z.J., 1999. Discriminant analysis and equivalent source localization of the EEG related to cognitive functions. Brain Topogr. 11 (4), 265–278. https://doi.org/10.1023/A:1022254519526.

Lindsley, D.B., Wicke, J.D., 1974. The electroencephalogram: autonomous electrical activity in man and animals. In: Bioelectric Recording Techniques. Elsevier, pp. 3–83. https://doi.org/10.1016/B978-0-12-689402-8.50008-0.

Linn, M.C., Petersen, A.C., 1985. Emergence and characterization of sex differences in spatial ability: a meta-analysis. Child Dev. 56 (6), 1479. https://doi.org/10.2307/1130467.

Lopes da Silva, F., 1991. Neural mechanisms underlying brain waves: from neural membranes to networks. Electroencephalogr. Clin. Neurophysiol. 79 (2), 81–93. https://doi.org/10.1016/0013-4694(91)90044-5.

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. https://doi.org/10.1080/02640410152475856.

Magosso, E., De Crescenzio, F., Ricci, G., Piastra, S., Ursino, M., 2019. EEG alpha power is modulated by attentional changes during cognitive tasks and virtual reality immersion, 2019 Comput. Intell. Neurosci. 1–18. https://doi.org/10.1155/2019/7051079.

Malhotra, N., Poolton, J.M., Wilson, M.R., Omuro, S., Masters, R.S.W., 2015. Dimensions of movement specific reinvestment in practice of a golf putting task. Psychol. Sport Exerc. 18, 1–8. https://doi.org/10.1016/j.psychsport.2014.11.008.

Manor, R., Cheaha, D., Kumarnsit, E., Samerphob, N., 2023. Age-related deterioration of alpha power in cortical areas slowing motor command formation in healthy elderly subjects. In 37 (2), 679–684. https://doi.org/10.21873/invivo.13128.

Marshall, P.J., Bouquet, C.A., Shipley, T.F., Young, T., 2009. Effects of brief imitative experience on EEG desynchronization during action observation. Neuropsychologia 47 (10), 2100–2106. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2009.03.022.

Marusic, U., Rakůsa, M., Guan, Y., Bai, S., Liu, W., 2021. The Visuospatial and Sensorimotor Functions of Posterior Parietal Cortex in Drawing Tasks: A Review. https://doi.org/10.3389/fnagi.2021.717002.

Mazaheri, A., 2010. Rhythmic pulsing: linking ongoing brain activity with evoked responses. Front. Hum. Neurosci. 4 https://doi.org/10.3389/fnhum.2010.00177.

McCrea, S., 2014. A neuropsychological model of free-drawing from memory in constructional apraxia: a theoretical review. Am. J. Psychiatr. Neurosci. 2 (5), 60. https://doi.org/10.11648/j.ajpn.20140205.11.

Milton, J., Solodkin, A., Hluštík, P., Small, S.L., 2007. The mind of expert motor performance is cool and focused. Neuroimage 35 (2), 804–813. https://doi.org/10.1016/j.neuroimage.2007.01.003.

Minarik, T., Berger, B., Sauseng, P., 2018. The involvement of alpha oscillations in voluntary attention directed towards encoding episodic memories. Neuroimage 166, 307–316. https://doi.org/10.1016/j.neuroimage.2017.10.064.

Mo, J., Liu, Y., Huang, H., Ding, M., 2013. Coupling between visual alpha oscillations and default mode activity. Neuroimage 68, 112–118. https://doi.org/10.1016/J.NEUROIMAGE.2012.11.058.

Morrone, J., Minini, L., 2023. The interlinking of alpha waves and visuospatial cognition in motor-based domains. Neurosci. Biobehav. Rev. 149, 105152 https://doi.org/10.1016/j.neubiorev.2023.105152.

Morrone, J.M., Pedlar, C.R., 2024. EEG-based neurophysiological indices for expert psychomotor performance – a review. Brain Cognit. 175, 106132 https://doi.org/10.1016/j.bandc.2024.106132.

Mulholland, T., 1995. Human EEG, behavioral stillness and biofeedback. Int. J. Psychophysiol. 19 (3), 263–279. https://doi.org/10.1016/0167-8760(95)00019-O.

Murata, A., 2005. An attempt to evaluate mental workload using wavelet Transform of EEG. Hum. Factors: The Journal of the Human Factors and Ergonomics Society 47 (3), 498–508. https://doi.org/10.1518/001872005774860096.

Neubauer, A.C., Fink, A., 2009. Intelligence and neural efficiency. Neurosci. Biobehav. Rev. 33 (7), 1004–1023. https://doi.org/10.1016/J.NEUBIOREV.2009.04.001.

Neubauer, A., Freudenthaler, H.H., Pfurtscheller, G., 1995. Intelligence and spatiotemporal patterns of event-related desynchronization (ERD). Intelligence 20 (3), 249–266. https://doi.org/10.1016/0160-2896(95)90010-1.

Neubauer, A.C., Grabner, R.H., Fink, A., Neuper, C., 2005. Intelligence and neural efficiency: further evidence of the influence of task content and sex on the brain–IQ relationship. Cognit. Brain Res. 25 (1), 217–225. https://doi.org/10.1016/J.COGBRAINRES.2005.05.011.

Neuper, C., Wörtz, M., Pfurtscheller, G., 2006. ERD/ERS patterns reflecting sensorimotor activation and deactivation. Prog. Brain Res. 159, 211–222. https://doi.org/10.1016/S0079-6123(06)59014-4.

Niedermeyer, E., Lopes da Silva, F.H., 1982. *Electroencephalography: Basic Principles, Clinical Applications, and Related Fields*, 5th ed. OUP USA.

Parks, R.W., Loewenstein, D.A., Dodrill, K.L., Barker, W.W., Yoshii, F., Chang, J.Y., Emran, A., Apicella, A., Sheramata, W.A., Duara, R., 1988. Cerebral metabolic effects of a verbal fluency test: a PET scan study. J. Clin. Exp. Neuropsychol. 10 (5), 565–575. https://doi.org/10.1080/01688638808402795.

Peng, Z., Xu, L., Wang, H., Song, T., Shao, Y., Liu, Q., Weng, X., 2022. The lateralization of spatial cognition in table tennis players: neuroplasticity in the dominant hemisphere. Brain Sci. 12 (12), 1607. https://doi.org/10.3390/brainsci12121607.

Petsche, H., Kaplan, S., Von Stein, A., Filz, O., 1997. The possible meaning of the upper and lower alpha frequency ranges for cognitive and creative tasks. Int. J. Psychophysiol. 26 (1–3), 77–97. https://doi.org/10.1016/S0167-8760(97)00757-5.

Peylo, C., Hilla, Y., Sauseng, P., 2021. Cause or consequence? Alpha oscillations in visuospatial attention. Trends Neurosci. 44 (9), 705–713. https://doi.org/10.1016/j.tins.2021.05.004.

Pfurtscheller, G., 1977. Graphical display and statistical evaluation of event-related desynchronization (ERD). Electroencephalogr. Clin. Neurophysiol. 43 (5), 757–760. https://doi.org/10.1016/0013-4694(77)90092-X.

Pfurtscheller, G., 1988. Mapping of event-related desynchronization and type of derivation. Electroencephalogr. Clin. Neurophysiol. 70 (2), 190–193. https://doi.org/10.1016/0013-4694(88)90119-8.

Pfurtscheller, G., 1992. Event-related synchronization (ERS): an electrophysiological correlate of cortical areas at rest. Electroencephalogr. Clin. Neurophysiol. 83 (1), 62–69. https://doi.org/10.1016/0013-4694(92)90133-3.

Pfurtscheller, G., 2003. Induced oscillations in the alpha band: functional meaning. Epilepsia 44 (s12), 2–8. https://doi.org/10.1111/j.0013-9580.2003.12001.x.

Pfurtscheller, G., Aranibar, A., 1977. Event-related cortical desynchronization detected by power measurements of scalp EEG. Electroencephalogr. Clin. Neurophysiol. 42 (6), 817–826. https://doi.org/10.1016/0013-4694(77)90235-8.

Pfurtscheller, G., Aranibar, A., 1979. Evaluation of event-related desynchronization (ERD) preceding and following voluntary self-paced movement. Electroencephalogr. Clin. Neurophysiol. 46 (2), 138–146. https://doi.org/10.1016/0013-4694(79)90063-4.

Pfurtscheller, G., Klimesch, W., 1992. Functional topography during a visuoverbal judgment task studied with event-related desynchronization mapping. J. Clin. Neurophysiol. 9 (1), 120–131. https://doi.org/10.1097/00004691-199201000-00013.

Pfurtscheller, G., Lopes da Silva, F.H., 1999. Event-related EEG/MEG synchronization and desynchronization: basic principles. Clin. Neurophysiol. 110 (11), 1842–1857. https://doi.org/10.1016/S1388-2457(99)00141-8.

Pfurtscheller, G., Neuper, C., 1994. Event-related synchronization of mu rhythm in the EEG over the cortical hand area in man. Neurosci. Lett. 174 (1), 93–96. https://doi.org/10.1016/0304-3940(94)90127-9.

Pfurtscheller, G., Neuper, C., Berger, J., 1994. Source localization using eventrelated desynchronization (ERD) within the alpha band. Brain Topogr. 6 (4), 269–275. https://doi.org/10.1007/BF01211172.

Pfurtscheller, G., Stancák, A., Neuper, C., 1996. Event-related synchronization (ERS) in the alpha band — an electrophysiological correlate of cortical idling: a review. Int. J. Psychophysiol. 24 (1–2), 39–46. https://doi.org/10.1016/S0167-8760(96)00066-9.

Pfurtscheller, G., Neuper, C., Flotzinger, D., Pregenzer, M., 1997. EEG-based discrimination between imagination of right and left hand movement. Electroencephalogr. Clin. Neurophysiol. 103 (6), 642–651. https://doi.org/10.1016/S0013-4694(97)00080-1.

Pollok, B., Krause, V., Butz, M., Schnitzler, A., 2009. Modality specific functional interaction in sensorimotor synchronization. Hum. Brain Mapp. 30 (6), 1783–1790. https://doi.org/10.1002/hbm.20762.

Possin, K.L., 2010. Visual spatial cognition in neurodegenerative disease. Neurocase 16 (6), 466–487. https://doi.org/10.1080/13554791003730600.

Quandt, L.C., Marshall, P.J., Bouquet, C.A., Young, T., Shipley, T.F., 2011. Experience with novel actions modulates frontal alpha EEG desynchronization. Neurosci. Lett. 499 (1), 37–41. https://doi.org/10.1016/j.neulet.2011.05.028.

Raimo, S., Santangelo, G., Trojano, · Luigi, 2021. The neural bases of drawing. A meta-analysis and a systematic literature review of neurofunctional studies in healthy individuals. Neuropsychol. Rev. 1, 3. https://doi.org/10.1007/s11065-021-09494-4.

Rilea, S.L., Roskos-Ewoldsen, B., Boles, D., 2004. Sex differences in spatial ability: a lateralization of function approach. Brain Cognit. 56 (3), 332–343. https://doi.org/10.1016/j.bandc.2004.09.002.

Ruff, C.C., Knauff, M., Fangmeier, T., Spreer, J., 2003. Reasoning and working memory: common and distinct neuronal processes. Neuropsychologia 41 (9), 1241–1253. https://doi.org/10.1016/S0028-3932(03)00016-2.

Rypma, B., D'Esposito, M., 1999. The roles of prefrontal brain regions in components of working memory: effects of memory load and individual differences. Proc. Natl. Acad. Sci. USA 96 (11), 6558–6563. https://doi.org/10.1073/pnas.96.11.6558.

Rypma, B., Berger, J.S., D'Esposito, M., 2002. The influence of working-memory demand and subject performance on prefrontal cortical activity. J. Cognit. Neurosci. 14 (5), 721–731. https://doi.org/10.1162/08989290260138627.

Rypma, B., Berher, J., Genova, H., Rebbechi, D., Desposito, M., 2005. Dissociating age-related changes in cognitive strategy and neural efficiency using event- related fMRI. Cortex 41 (4), 582–594. https://doi.org/10.1016/S0010-9452(08)70198-9.

Sauseng, P., Klimesch, W., Doppelmayr, M., Pecherstorfer, T., Freunberger, R., Hanslmayr, S., 2005. EEG alpha synchronization and functional coupling during top-down processing in a working memory task. Hum. Brain Mapp. 26 (2), 148–155. https://doi.org/10.1002/hbm.20150.

Schneider, W., Shiffrin, R.M., 1977. Controlled and automatic human information processing: I. Detection, search, and attention. Psychol. Rev. 84 (1), 1–66. https://doi.org/10.1037/0033-295X.84.1.1.

Singer, Robert N., Murphey, Milledge, Keith Tennant, L., 1993. Handbook of Research on Sport Psychology. Macmillan ; Collier Macmillan Canada ; Maxwell Macmillan International, New York, Toronto, New York. ©1993.

Smith, M.E., McEvoy, L.K., Gevins, A., 1999. Neurophysiological indices of strategy development and skill acquisition. Cognit. Brain Res. 7 (3), 389–404. https://doi.org/10.1016/S0926-6410(98)00043-3.

Steriade, M., Llinás, R.R., 1988. The functional states of the thalamus and the associated neuronal interplay. Physiol. Rev. 68 (3), 649–742. https://doi.org/10.1152/physrev.1988.68.3.649.

Vijn, P.C.M., van Dijk, B.W., Spekreijse, H., 1991. Visual stimulation reduces EEG activity in man. Brain Res. 550 (1), 49–53. https://doi.org/10.1016/0006-8993(91)90403-I.

Wang, K.P., Cheng, M.Y., Chen, T.T., Huang, C.J., Schack, T., Hung, T.M., 2020. Elite golfers are characterized by psychomotor refinement in cognitive-motor processes. Psychol. Sport Exerc. 50, 101739 https://doi.org/10.1016/J.PSYCHSPORT.2020.101739.

Weiss, M.S., 1989. Testing EEG data for statistical normality. Images of the Twenty-First Century. Proceedings of the Annual International Engineering in Medicine and Biology Society 704. https://doi.org/10.1109/IEMBS.1989.95942. –705.

Wianda, E., Ross, B., 2019. The roles of alpha oscillation in working memory retention. Brain and Behavior 9 (4), e01263. https://doi.org/10.1002/brb3.1263.

Womelsdorf, T., Fries, P., 2007. The role of neuronal synchronization in selective attention. Curr. Opin. Neurobiol. 17 (2), 154–160. https://doi.org/10.1016/j.conb.2007.02.002.

Yuan, Y., Brown, S., 2015. Drawing and writing: an ALE meta-analysis of sensorimotor activations. Brain Cognit. 98, 15–26. https://doi.org/10.1016/J.BANDC.2015.05.004.

Zhang, J., Shi, Y., Wang, C., Cao, C., Zhang, C., Ji, L., Cheng, J., Wu, F., 2021. Preshooting electroencephalographic activity of professional shooters in a competitive state. Comput. Intell. Neurosci. 1–9. https://doi.org/10.1155/2021/6639865, 2021.

Zhuang, P., Toro, C., Grafman, J., Manganotti, P., Leocani, L., Hallett, M., 1997. Event-related desynchronization (ERD) in the alpha frequency during development of implicit and explicit learning. Electroencephalogr. Clin. Neurophysiol. 102 (4), 374–381. https://doi.org/10.1016/S0013-4694(96)96030-7.