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Review Article

Artigo de Revisão

Neural Correlates of Shooting Sports Performance: A Systematic Review on Neural Efficiency Hypothesis

Correlações neurais do desempenho do tiro esportivo: uma revisão sistemática sobre a hipótese da eficiência neural

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Abstract

Introduction: Shooting is an ancient sport modality and requires mental, emotional, and cognitive aptitudes. Shooting is an ancient sport that requires mental, emotional, and cognitive skills of the practitioner.

Objective: In this comprehensive systematic review we sought to examine the hypothesis of neural efficiency in shooting sports (rifle, pistol and archery) related to performance.

Methods: We perform the search in PubMed database using the terms "*brain* and *shooting*". After applied the study criteria, 28 articles participated in this review.

Results and Discussion: There are consistent differences between expert and novice shooters in cortical activity related to shooting performance, which imply that shooting expertise leads to brain adjustments to safe energy during the task and correlates with performance. The hemispheric laterality implies that experts present high attentional focus degree.

Conclusion: The literature shows that there are specific differences on expert and novice shooters' mapping brain during shooting tasks. Moreover, increasing in Alpha frequency at aiming period and pulling the trigger moment at left temporal (T3) together with stability at right temporal (T4) sites relates to performance. Furter findings were discussed.

Keywords: neuroscience; target shooting; high-performance sports; brain mapping; motor behavior.

Resumo

Introdução: O tiro é uma modalidade esportiva milenar que requer requires aptidões mentais, emocionais e cognitivas de seu praticante.

Key points

- There were consistent differences between expert and novice shooters in cortical activity.

- Those differences related to sportive shooting performance.

- The hemispheric laterality implies that experts present high attentional focus degree.

Pontos-Chave Destaque

- Houve diferenças consistentes entre atiradores experientes e novatos na atividade cortical.

- Essas diferenças estão relacionadas ao desempenho esportivo do tiro.

- A lateralidade hemisférica implica que os especialistas apresentam alto grau de foco atencional.

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Objetivo: Nesta revisão sistemática abrangente procuramos examinar a hipótese de eficiência neural em esportes de tiro (rifle, pistola e tiro com arco) relacionados ao desempenho.

Métodos: Realizamos a busca nas bases de dados PubMed e Google Scholar utilizando os termos "*brain and shooting*". Após aplicados os critérios do estudo, 28 artigos participaram desta revisão.

Resultados e Discussão: Existem diferenças consistentes entre atiradores experientes e iniciantes na atividade cortical relacionada ao desempenho do tiro, o que implica que a experiência do tiro leva a ajustes cerebrais para energia segura durante a tarefa e se correlaciona com o desempenho. A lateralidade hemisférica implica que os experts apresentam alto grau de foco atencional.

Conclusão: A literatura mostra que existem diferenças específicas no mapeamento cerebral de atiradores experientes e novatos durante tarefas de tiro. Além disso, o aumento da frequência Alpha no período de mira e o momento de disparo em T3, juntamente com a estabilidade nos locais T4, relacionam-se ao desempenho. Outros achados foram discutidos.

Palavras-chave: neurociência, tiro ao alvo, esportes, mapeamento cerebral, comportamento motor.

Neural Correlates of Shooting Sports Performance: A Systematic Review on Neural Efficiency Hypothesis

Introduction

Shooting sports are practiced since the first modern Olympic Games edition in 1896(1), and the fundamental techniques are the stable position; breath control; constancy in focusing the sight; and trigger activation time. Thus, the individual must present sufficient motor skill and balance to reach the center of the target(2). The scientific interest on how human brain works is registered since 18th century(3). In recent decades, Neuroscience research on human intelligence increased aiming to examine brain functioning together with the nervous system aiming to clarify how neuronal structures are recruited in motor actions learning processes(4–7). Furthermore, such investigation also relates to behaviors, thoughts, and sensations.

Haier *et al.*(8) postulated a theory that individuals with higher intelligence scores exhibited lower energy consumption of the brain when compared to individuals with lower intelligence scores for accomplishment of tasks. That theory known as neural efficiency relates to economy in brain energy expenditure in cortical processes during specific tasks. One of the most important factors related to neural efficiency concept is the task difficulty level. In complex tasks, such as those related to decision making, emotional knowledge, or tasks preceded by learning, brain activation is lower comparing to easier tasks(9,10). In more intelligent individuals, increasing task difficulty leads to greater cerebral activation when compared to less intelligent ones(10). Brain regions related to intelligence are parietal and frontal cortexes(11). The concept of neural efficiency also applies to tasks related to movement. All motor skills are composed of contributions from both motor and cognitive elements, which are also called perceptual and motor skills(12,13). High performance motor tasks relate to efficient cortical processing(12). Hence, sensory-motor integration is closely related to neural efficiency. Sensory afferences assists the human motor system preparation improving the execution of fine motor skill activities(14). Various sources of sensory information are available for the human motor system. Thus, there are several different ways on how the central nervous system process information in skillful movement(15).

In several activities, higher performance relates to decreasing in cortical activation, which is exhibited immediately prior to the task execution(8,16,17). Such effect was observed in professional pianists, who completed a motor task involving finger movements with less cortical activity than the less skilled pianists(18) and suppression of visual stimuli related to performance in basketball expert performers(19).

Investigating how the brain works while shooting can help clarify important aspects of human behavior and according to the neural efficiency postulate, saving energy in cognitive processes relates to sports performance. To better understand brain functioning related to target shooting it is important to gather current knowledge on the issue. Thus, the objective of the present study was to review the research focusing on the neural efficiency hypothesis related to target shooting performance.

Methods

The present study is a systematic review that consulted the PubMed database. Three researchers proceeded the search using the following terms: "*brain* and *shooting*", with no time delimitation. Inclusion criteria were studies that examined shooting sports and focused cortical activity. Exclusion criteria were not focused on target shooting with pistol, rifle, or archery, not investigated the relation of cortical activity with shooting performance. Additionally, studies that addressed diseases were excluded as well, and full texts that were not published in English or Portuguese were withdrawn.

Results and Discussion

Initially, 277 articles were found. From those, 185 were withdrawn because did not focused archery, pistol, or rifle shooting. From the 92 studies, 64 were withdrawn because did not address shooting performance. Thus, 28 articles participated in this review (Figure 1). Table 1 shows results on evidence of neural efficiency in.

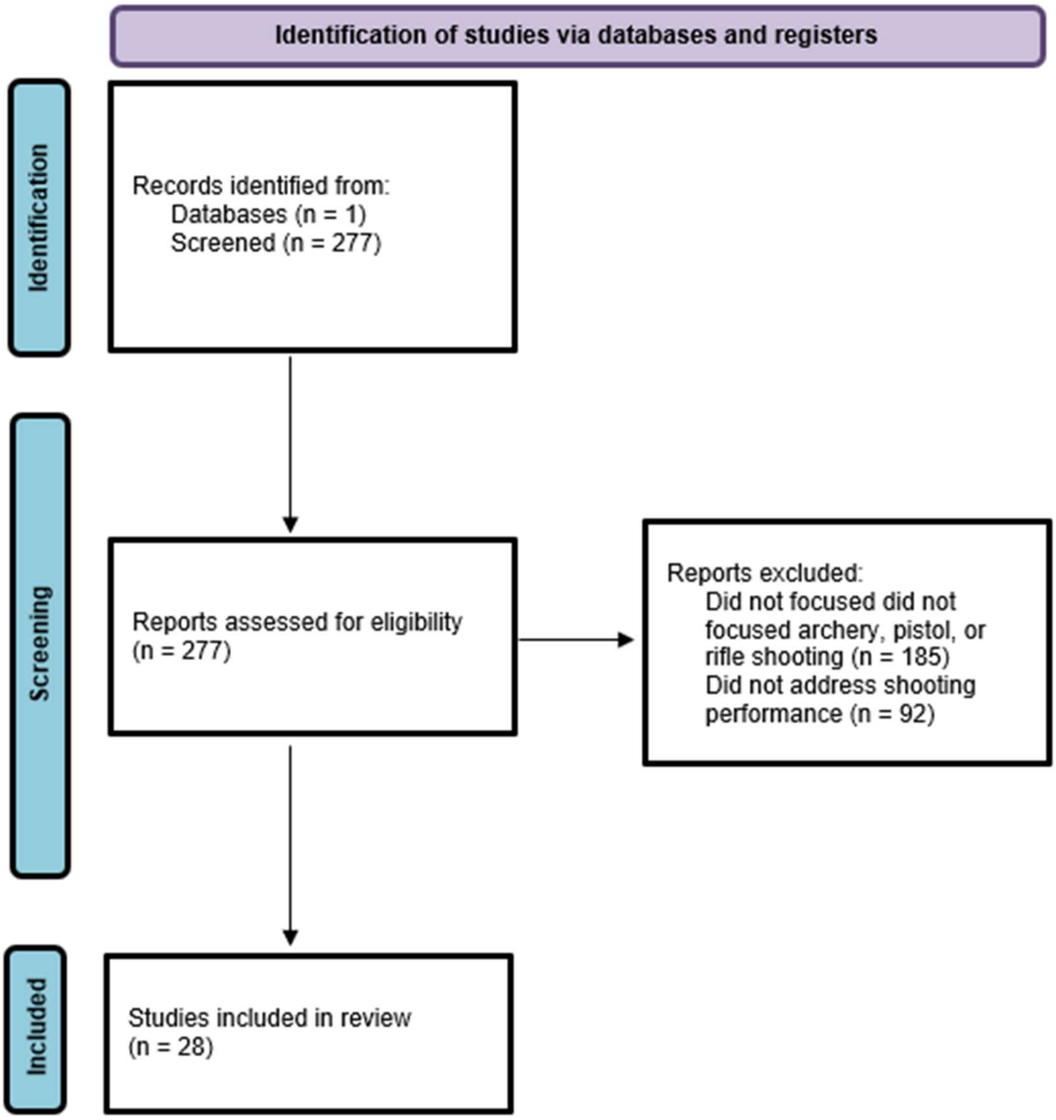

Figure 1 – Selection process for participant studies according to the inclusion and exclusion criteria.

Table 1 – Literature review results on neural efficiency by cortical activity relate to shooting sports performance

Author	Year	Modality	Focus	Results
				Brain activity and shooting performance
Hatfield *et al*.(20)	1984	Rifle shooting	Electroencephalographic profile on cognitive processes during self-paced motor performance in marksmen: Alpha waves activity (8-12 Hz) at T3, T4, O1, and O2 sites at the 7.5-0 sec pre-shot period.	High activity (low Alpha waves) in right brain and low activity (High Alpha waves) in left brain in marksmen.
Salazar *et al*.(21)	1990	Archery	Hemispheric asymmetry – Alpha (12 Hz) and Beta (28 Hz) power at T3, T4 sites, cardiac response, and performance in elite archers at the 3-0 sec pre-shot period.	Increasing at high-Alpha (12 Hz) and Beta (28 Hz) power at 3-1 sec before the shot related to worst shots in elite archers.
Konttinen & Lyytinen(22)	1992	Rifle shooting	Brain slow waves (< 1 Hz) preceding triggering in marksmen and novices' rifle shooters[a]. Slow potentials (SP) at C3, C4, and OZ areas.	Negative SPs related (increased cortical activation) to worst shots.
Konttinen & Lyytinen(23)	1993	Rifle shooting	Brain slow waves (< 1 Hz) preceding time-locked visuo-motor performance in rifle shooters related to rifle stabilization[a]. SP at Fz, C3, C4, and Oz areas during aiming time.	At visual aiming shooters presented SP negativity. The individual SP patterns predicts shooting performance.
Landers *et al*.(24)	1994	Archery	Effects of learning on symmetry between temporal regions (T3 and T4) at Alpha waves (8 – 12 Hz) and electrocardiographic patterns in novice archers with pre arrow release period of 3 sec.	Greater increase of Alpha waves in left hemisphere; not observed in right hemisphere. Those hemispheric activity asymmetries were related to 62% increasing in shooting performance. Increasing at High-Alpha (12 Hz) waves at 1 - 0.5 sec pre-shot time was related to worst shots.
Konttinen *et al*.(25)	1995	Rifle shooting	Brain slow potentials at Fz, C3, C4, and Oz areas, with rifle not fixed related to successful performance.	SP positivity at Fz together with central-right (C4) SP negativity higher than at C3. Less cortical activation was associated with successful performance.

Author	Year	Modality	Focus	Results
				Brain activity and shooting performance
Hillman *et al*.(26)	2000	Rifle shooting	Comparing the electrocortical activity of executed and rejected shots in skilled marksmen: Alpha and Beta spectral power at F3, F4, C3, C4, T3, T4, P3, and P4 regions, for the 4 sec period prior to the execution or rejection of shots.	Comparing with executed shots, in rejected shots there was progressive increase in Alpha and Beta power in both hemispheres.
Haufler *et al*.(27)	2000	Rifle shooting	Power spectral symmetry estimated at 6-7 Hz (Theta), 9-11 Hz (Alpha),18-22 Hz (Beta), and 36-44 Hz (Gama) at F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2 areas, during the aiming period (6 sec) in skilled marksmen and novice rifle shooters.	Marksmen exhibited less cortical activation (increased Alpha power) than the novice shooters at all sites during the aiming period with a pronounced difference in the left central-temporal-parietal area. Less cortical activation in left hemisphere was related to better performance.
Janelle *et al*.(28)	2001	Rifle Shooting	Symmetry in cortical activation (Alpha and Beta power) and gaze behavior (ocular activity) during rifle shooting in experts and non-experts' shooters during the pre-shot periods (1 sec).	Experts exhibited significant increase in left-hemisphere Alpha and Beta power, together with a reduction in right-hemisphere Alpha and Beta power. Higher Alpha and Beta power in left hemisphere related to better shooting performance.
Loze *et al*.(29)	2001	Air pistol shooting	Alpha power reactivity during pre-shot time (3-1 sec) at central-occipital (Oz) and temporal (T3, T4) areas related to performance in experts air-pistol shooters during 1–3 sec before the shot.	Occipital EEG Alpha power increasing before best shots (1-3 sec) while gradually decreases before worst shots. Less cortical activity at OZ site at the pre-shot period related to best shots and more cortical activity related to worst shots.
Deeny *et al*.(30)	2003	Rifle Shooting	Electroencephalographic coherence at low-Alpha (8–10 Hz), high-Alpha (10–13 Hz) and low-Beta (13–22 Hz) bands at F3, Fz, F4, C3, Cz, C4, T3, T4, P3, Pz, P4, O1, and O2 sites during aiming period (4 sec) prior to trigger pull in expert marksmen and skilled rifle shooters.	Compared with skilled shooters, the expert marksmen exhibited lower coherence among the sites observed. Marksmen presented better performance than skilled shooters, as expected.

Author	Year	Modality	Focus	Results
				Brain activity and shooting performance
Kerick *et al*.(31)	2004	Air pistol shooting	Cerebral cortical adaptations in novice pistol shooters after 12-14 training weeks. Event-related Alpha-power at F3, Fz, F4, C3, Cz, C4, T3, T4, P3, Pz, and P4 areas during aiming periods (5 sec).	Increased Alpha-power in learning processes. There were curvilinear relations between both temporal sites (T3, T4) and both the long-term and short-term measures of performance: means in training season and in tests (three test periods).
Doppelmayr *et al*.(32)	2008	Rifle Shooting	Fontal midline Theta (Fz, Cz, Pz, Oz) in experts and novices during 3 sec aiming period.	There was significantly stronger Theta activity and better performance for experts comparing to novices.
Hung *et al*.(33)	2008	Rifle Shooting	Visuomotor expertise and complexity of cerebral cortical activity at ten brain sites (F3, F4, C3, C4, T3, T4, P3, P4, O1, O2) in experts and novices riffle shooters in 5 sec aiming period.	Visuomotor expertise was inversely related to the complexity on the cerebral cortical activity and to shooting performance.
Kim *et al*.(34)	2008	Archery	fMRI was used to examine brain activity during the aiming period in elite and novice archers.	In experts, the occipital gyrus and temporal gyrus were activated during aiming period. In novices, the frontal area was the main area activated.
Deeny *et al*.(35)	2009	Rifle shooting	Cortical coherence between frontal sites (F3 and F4) and central (C3, C4), temporal (T3, T4), parietal (P3, P4), and occipital (O1, O2) regions, during aiming period (4 sec) in experts and novices riffle shooters.	Compared to novices, experts generally exhibited lower coherence, mainly in right hemisphere.
Del Percio *et al*.(36)	2009	Air pistol shooting	Changes in Alpha rhythms (amplitude of low-Alpha and high-Alpha waves – desynchronization/synchronization: F3, F4, C3, C4, P3, P4, O1, and O2 sites in visuo-attentional and sensorimotor task: during pre-shot period (3 sec) in air pistol athletes' and non-athletes related to performance.	In elite athletes, low- and high-Alpha event related desynchronization was lower than in the shooters non-athletes over the whole scalp. Related to performance, the amplitude of event-related synchronization was larger for high score shots than for low score shots among elite athletes in right parietal and left central areas.

Author	Year	Modality	Focus	Results
				Brain activity and shooting performance
Del Percio *et al*.(37)	2011	Air pistol shooting	Event related coherence spectral analysis (F3: C3, T3, P3, and O1; F4: C4, T4, P4, and O2) of brain waves rhythms (Theta, low-Alpha, high-Alpha, low-Beta, high-Beta, and Gamma) in athletes and non-athletes before visuomotor performance (aiming period).	Coherence amplitude was stable in athletes but not in non-Athletes in intra-hemispheric values: low-Alpha (parietal-temporal and parietal-occipital regions), high-Alpha (parietal-temporal and parietal-occipital regions), high-Beta, and Gamma (parietal-temporal regions); and in inter-hemispheric values: low-Alpha (parietal regions), high-Alpha (parietal regions), high-Beta, and Gamma (parietal-temporal regions).
Kim *et al*.(38)	2014	Archery	fMRI study of differences in brain activity among elite, expert, and novice archers at aiming period.	Regions of brain activity differed by group as a function of skill level: there were differences according to the three skill levels studied.
Bertollo *et al*.(39)	2016	Air pistol shooting	Theta and Alpha event-related synchronization / desynchronization in shooting performance.	The MAP model used to classify optimal-automatic performance showed to be related to shooting performance and can be a useful tool to improve it.
Di Fronso *et al*.(40)	2016	Air pistol shooting	Neural markers of shooting pistol performance states: an Olympic athlete case study.	The MAP model analysis of desynchronization/synchronization showed that global synchronization of cortical arousal was related to shooting performance.
Gallicchio *et al*.(41)	2016	Rifle shooting biathlon	Shooting under cardiovascular load: Electroencephalographic activity in preparation for biathlon shooting in experienced athletes.	Under cardiovascular load, shooting performance did not change.
Gong *et al*.(42)	2017	Rifle shooting	Resting state and shooting performance.	Coherence in Beta band of C3 e T3 and of length of the Theta band brain network in resting-state with shooting performance were related to shooting performance

Author	**Year**	**Modality**	**Focus**	**Results**
				Brain activity and shooting performance
Woo & Kim(43)	2017	Air pistol shooting	Competitive and practice states inter- and intrahemispheric coherences in young athletes.	Interhemispheric coherence during aiming was higher under competition.
Gong *et al*.(44)	2018	Rifle shooting	Relationship between brain network and shooting performance during shooting aiming.	Beta 1 and Beta 2 bands at the closest time window of firing time were related to performance.
Zhang *et al*.(45)	2019	Rifle shooting	Brain function network in experts and in novices.	Alpha and Beta waves between P3 and C3. Left areas are distinguished between experts and novices.
Gong *et al*.(46)	2020	Pistol shooting	Effects of neurofeedback training on shooting performance in non-expert shooters.	The sensory-motor rhythm group presented significant shooting performance improvement comparing to Alpha and control groups.
Zhang *et al*.(47)	2021	Rifle shooting	Theta, Alpha, and Beta power on noncompetitive and competitive states in national athletes, correlation analysis between EEG power and shooting performance.	There was a significant linear correlation between shooting performance and prefrontal, central, temporal, and occipital regions in the Beta band.

cortical activity related to shooting sports performance exhibited in the literature. Rifle shooting was the most frequent modality (n=16; 64,3%), followed by pistol shooting (n=08; 28,6%) and archery (n=04; 14,29%).

Changes in cortical activity captured by EEG express increasing and/or decreases of power in frequency bands in certain brain regions(48,49) and there are some analyses that may provide a better understanding of the phenomena of brain functioning such as: hemispheric asymmetry, synchronization / desynchronization, and coherence. Asymmetry is the difference between left and right cortical activity in homologous sites(50). Synchronization is a mechanism for large-scale integration in the brain since cortical integration processes may involve entire brain regions(51,52). Coherence is a measure that evaluates the degree of linear correlation from two cortical regions, for a given band from two time series, which reflects communication between different areas(30). Thus, low coherence indicates regional autonomy (or independence)(30,53). The results of the present study showed that the Alpha and Beta waves mainly presented significant differences in coherence according to learning and practice in left hemisphere, which related to performance.

According to the literature, the precise ranges associated with the waves vary across studies(54). Hence, we present here most common categorization found in the literature. The electrocortical brain activity is measured in hertz (Hz) and occurs in different frequencies (waves): Delta (<4 Hz), Theta (4–7 Hz), low-Alpha (8–10 Hz), high-Alpha (11-13 Hz), low-Beta (14–22 Hz), high-Beta (23-35 Hz), and Gamma (36–44 Hz)(35,55). The relationship between brain waves and behavior is evident in the literature. Hatfield *et al*.(20) explained that Theta waves (4-8 Hz) are associated with a relaxed, drowsy state; Absolute alpha power (8-12 Hz; 8-13 Hz) is associated with a relaxed but alert state of consciousness, and Beta waves (12-32 Hz) are indicative of active mental processing.

Performance in shooting is subjacent in marksmen. Hatfield et. al(20) investigated the electroencephalographic profile during self-paced task in rifle marksmen in three 2.5 seconds (sec) EEG epochs: 7.5-5.0 sec (epoch 1); 5.0-2.5 sec (epoch 2); and 2.5-0.0 sec (epoch 3). During the shooting task, at epoch 2, there was an increase in right-brain activity – which means low Alpha waves activity and continued up to the trigger pull time (epoch 3). The authors explained that the right-brain relates to motor tasks because it is involved in visual-spatial and kinesthetic processes and the difference between right temporal (T4 electrode) and left temporal (T3 electrode) areas – that relates to verbal and analytical processes. Left-brain presented increased Alpha waves (8-12 Hz) activity (low cortical activation). Those findings showed asymmetry between T3 and T4 at Alpha band was related to high performance indicating that marksmen presented high degree of attentional focus favoring them to "effectively reduce the conscious mental activity of the left cerebrum, thus reducing any distracting cognitions"(20).

After 14 weeks of training, Salazar *et al*.(21) observed at the central-temporal regions in elite and novice archers that Alpha activity was the dominant frequency during the aiming period. In elite archers, there was a significant declining in activation level in the left hemisphere comparing with the right hemisphere. From three sec before the archery shot, there were no differences in right hemisphere whereas there were significant increases at 10, 12 and 24 Hz in left hemisphere. Such effect can be due to the marksmen skillfulness to reduce left-hemisphere processes(20). Furthermore, focusing shooting performance, the authors examined brain activity before (3-1 sec) the shot. There was greater power in the left hemisphere at Theta (6 Hz), high-Alpha (12 Hz), and Gama (28 Hz) related to the worst archery shots showed comparing to best shots. They suggested that greater activation at those frequencies is unfavorable to performance. In line with such findings, Landers *et al*.(56) examined the effects of archery learning on electroencephalographic and electrocardiographic patterns in novice individuals and found greater increase of Alpha waves in left hemisphere after the learning period, effect that was not observed in right hemisphere. Such asymmetries in hemispheric activity were related to a 62% increase in performance. Moreover, at 0.5 second before the arrow release, increasing at high-Alpha (12 Hz) waves activity in left hemisphere was related to worst shots.

Slow potentials (SPs) are electrocortical waves below 1Hz(51), which correlate with immediate processing of sensory inputs. Konttinen & Lyytinen(22,23,25) examined a specific event-related potentials (ERPs) that are longer than SPs related to rifle shooting performance. Negative SP indicates increasing in cortical activation, while a positive SP indicates decreasing in activation(25). In marksmen rifle shooters, the authors found that at aiming time negative SP brain was significantly greater in worst shots compared with the best shots(22).

In another study(23), they found a decrease in negative SP preceding the trigger pull in rifle-shooting related to successful shots in marksmen, which was not observed in novices(23). Additionally, examining the medial-frontal (Fz), medial-central (Cz) and medial-occipital (Oz) areas with rifle partially fixed, Konttinen & Lyytinen(25) found that for high-scoring shot there was increasing in SP positivity at pre-shot at Fz and Cz areas, which express decrease in cortical activity and reflects the behavior searching for balance in holding and stabilizing the rifle immediately before the shot. Theirs findings demonstrated that frontal (Fz) SP positivity was associated with successful performance, but only if Oz was neutral, and SP at C4 was more negative than C3. Those results showed that such specific asymmetry is important to shooting performance.

Also, in rifle shooting, Hillman *et al.*(26) examined the Alpha and Beta spectral power at the pre-shot period (4 seconds) compering cortical activity of shot executed with shot withdrawn. For rejected shots, they found progressive increase in Alpha and Beta power compared with executed shots, in both hemispheres. They found same changes in Beta power in both hemispheres. The authors discussed that such findings diverged from classical previous EEG interpretations, which stated that increases in Alpha power are expected to be accompanied by decreases in Beta power and vice-versa(26,48). Furthermore, they explained that increases in Alpha and Beta power indicates increasing in intracortical communication, thus higher energy was expended in processing. Hence, increased neuronal activity was observed for rejecting shots comparing with executing shots. This study which examined the self-paced behavior of the shooter is a great contribution because relates to the competition scenario helping to clarify the brain functioning during that specific real competitive scenario.

Haufler *et al.*(2000) evaluate the cortical symmetry – where a score off 0 (zero) for any of the EEG bands shows that power is equivalent in both left and right homologous sites. The authors explained that Beta and Gama power are directly related to cortical activation, whereas Theta and Alpha power are inversely related to activation. In that study, the data were examined according to frequencies Theta waves (6-7 Hz), low-Alpha waves (9 Hz), high-Alpha waves (10-11 Hz), Beta waves (18-22 Hz), and Gama Waves (33-44 Hz) at F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2 sites during aiming period (6 sec) in marksmen and novice rifle shooters. Results showed that in shooting task at Theta waves, marksmen presented significant more hemispheric power than novices and there were no differences in hemispheric asymmetry. At low-Alpha waves, marksmen presented more power at T3, P3, and O1 sites, whereas there were no statistically significant differences at the homologous sites nor at F3, F4 and C3, C4 regions. Furthermore, marksmen presented lower asymmetry than novices at T3 and T4 sites. At high-Alpha waves, there was significant more power at P4 site in marksmen than in novices. Marksmen presented lower asymmetry than novices at T3 and T4. At Beta waves, marksmen presented significant more power hemispheric than novices, except at T3 region. Marksmen exhibited lower asymmetry at C3, C4, T3, and T4 sites than novices. Furthermore, at Gamma waves, marksmen exhibited less power than novices in all cortical regions and presented lower asymmetry at C3, C4, T3, and T4 regions than novices. As expected, marksmen presented significant better performance in shooting than novices. During the aiming period (6 seconds before the shot) comparing to novices, experts exhibited less cortical activation. The authors discussed that marksmen presented more proficiency in facing the specific visuospatial challenge in which they were highly trained. The spectral differences observed in the frontal area indicate sustained attention and suggested that they are deeply involved with the task and economically allocate their cortical resources(27), which related to better shooting performance. Those findings are in line with the neural efficiency hypothesis.

Jannelle *et al.*(28) compared Alpha power across the left and right hemisphere in rifle shooting and found significant increases in the left hemisphere in elite athletes. For whom the pre-shot (1 second) periods were characterized by increases at the left hemisphere Alpha and Beta power and reduced levels of Alpha and Beta power at the right hemisphere, and nonexperts exhibited similar asymmetry, albeit to a lesser extent. In line with previous studies, the authors explained that lower band activity is quite relevant in performance context(25,53) and those lower frequencies are involved in global cortico-cortical communication within the brain(26). Moreover, asymmetry between hemispheres related to shooting performance(28).

Loze et. al. (29) examined the occipital (Oz) and temporal (T3 and T4) activity during aiming period (6 seconds pre-shot) in air-pistol shooting. Results showed that, before the best shots, the occipital Alpha power increased, but decreased before worst shots and, at the last pre-shot epoch (2 seconds), the magnitude was significantly greater for best shots. The authors concluded that there was lessening in cognitive processing during aiming period in experts' shooters. Furthermore, before the best shots, visual attention was suppressed. The Alpha power increased for occipital region during epochs 1±3 before best shots but decreased before worst shots, thus, on the one hand, visual attention to the pistol and target was progressively suppressed, on the other hand, to increase aim-related visual information processing in the pre-shot period related to performance decreasing(29). Those findings corroborate the neural efficiency theory and highlights the correlation of increasing at Alpha waves with performance in target shooting.

Examining coherence, Deeny *et al.*(30) demonstrated reduction in communication between T3 and Fz regions in marksmen rifle shooters, supporting the neural efficiency postulate. They compared marksmen with skilled shooters' electroencephalographic coherence at low-Alpha (8–10 Hz), high-Alpha (10–13 Hz) and low-Beta (13–22 Hz) bands at F3, Fz, F4, C3, Cz, C4, T3, T4, P3, Pz, P4, and O1, O2 sites during aiming period: 4 seconds prior to trigger pull. Table 2 presents the significant coherence differences between experts and skilled rifle shooters.

Table 2 – Significant coherence differences between expert marksmen and skilled shooters(30)

Waves	Regions	Coherence in marksman*
Low-Alpha (8-10 Hz)	Temporal (T3) – Frontal (Fz)	↓
High-Alpha (10-13 Hz)	All left hemisphere areas (C3, P3, T3, O1) – Frontal (Fz)	↓
Low-Beta (13-22 Hz)	Temporal (T3) – Central (Fz, Cz, Pz)	↓

From Deeny *et al.*(30) results. *Coherence in marksmen comparing to skilled shooters.

The expert marksmen exhibited lower coherence among the sites observed: a) At low Alpha band – for T3 and Fz regions; b) At high Alpha band – between all left hemisphere regions (C3, P3, T3, O1) and (Fz); and c) At low Beta band – between T3 and all midline regions (Fz, Cz, Pz). Spectral power did not present significant differences, because of the similar technical level of the shooters. The authors discussed that since results between groups (marksmen x skilled shooters) showed no significant differences in coherence for low-Beta waves (13-22 Hz) – that relates to alertness, at any site paired with Fz it was highlighted the relevance of the special relationship between the left-temporal and motor regions for expertise in shooting(30). They added that learning stages relates to unstable neural processes, which diminish as skill increases and movements progress to more refined, steady, and automatic and it is reflected in performance. Furthermore, they pointed out that the coherence levels of the expert marksmen, compared to less skilled shooters, indicated decrease in left hemispheric communication as well suppression of the analytical processing, which would lead to uncomplicate the task execution.

Kerick *et al.*(31) examined the cortical adaptations for event-related Alpha-power in novice pistol shooters after 12-14 training weeks in three tests. They observed significant increase in Alpha-power in left temporal region (T3) comparing test 1 to test 3. In relation to performance, there were curvilinear relations of event-related Alpha power between Alpha power and both temporal sites (T3, T4) with both the long-term and short-term measures of performance (means of scoring in training season and in tests). Those findings reflect task-related chronic neural adaptations and acute performance states. The authors discussed that performance in relation to brain activity can be described as an inverted-U: better performance relates to increasing synchrony of cortical activation up to a certain point beyond which further synchrony will be associated with a performance decay. Furthermore, results indicate that cortical activity relates to sensorimotor integration and automaticity leads to less cognitive effort corroborating the neural efficiency hypothesis.

Doppelmayr *et al.*(32) through functional magnetic resonance imaging (fMRI) compared the frontal midline ((Fz, Cz, Pz, Oz) Theta activity in experts and novice' shooters. Results showed significant increased Theta power at anterior cingulate area and at frontal midline cortex, which reflected steady state, only in experts. Difference was strong and significant at the second three before the shot. Such findings demonstrated that focused attention regions (anterior cingulate area and medial frontal cortex) during aiming period work differently in experts and in novices. The authors detailed that while novices were incapable to center attention exactly to the triggering time point, while experts do so very well.

The correlation dimension (D2) is an analysis useful to non-symmetric objects (fractal dimension)(57) such as brain activity. Hung *et al.*(33) used the D2 to examine the inverse correlation of the visuomotor expertise with the complexity of the cortical activity in rifle shooters related to performance. Experts exhibited lower D2 comparing to novices and there was inverse correlation of D2 and accuracy in shooting. According to the authors, those results indicated that higher cortical complexity contributed to the "noise" in the brain leading to lower accuracy. From those findings, they concluded that refinement and efficiency of cortical activity contributes to visuomotor performance. The authors highlighted that although using nonlinear metric to examine brain activity, results were in line with other studies that used linear methods such as spectral signal analysis.

Kim *et al.*(34) used a fMRI scanner to examine brain activity during the aiming period in elite and novice archers. The elite archers were at the highest level of performance (world class). Results showed that in experts, the occipital gyrus and temporal gyrus were activated during aiming period and in novices, the frontal area was the main activated area. Those findings were related to archery performance.

Focusing coherence, Deeny *et al.*(35) found differences according to frequency bands between expert and novice rifle shooters. The authors examined cortical activity at four, three, two, one sec at aiming period (before shot). The coherence in experts were lower in all comparisons between expert and novice rifle shooters. As expected, expert's performance results on target points were significantly better (339.8±44.7) comparing to novices (90.7±39.8). and, in experts, coherence was positively associated with aiming movement variability. Those findings indicate that lower coherence relates to lower aiming variability and to better shooting performance. The authors also investigated the directionality of cortico-cortical communication using phase angles analysis. The results showed that in experts shifted phase angle were more negative between frontal and posterior areas in low frequencies (Table 3). In novices, there was a more positive phase angle in the midrange frequencies. The authors concluded that, comparing to novices, there is enhancement of cortical networks in experts, which exhibited different strategies "related to memory processes and executive influence over visual-spatial cues"(35).

Pfurtscheller & Silva (49) examined the synchronization and desynchronization of the electrical cortical activity. They explain that an event can be internally or externally paced and both results in the generation of an event-related potential (ERP) and a change in the ongoing EEG as an event-related desynchronization (ERD) or event-related synchronization (ERS). ERP and ERD/ERS are different responses of neuronal structures in the brain: the ERP is phase-locked and the ERD/ERS is not phase-locked to the event. The main difference between those phenomena is that "the ERD/ERS is highly frequency band-specific, whereby either the same or

Table 3 – Significant coherence in frontal (executive regions) and other cortical regions, differences between experts and novices rifle shooters (35)

Waves	**Regions**	**Coherence in experts***
Low-Alpha (8-10 Hz)	F4-T4	↓
High-Alpha (11-13 Hz)	F3-T3	↓
Low-Beta (14-22 Hz)	F3-T3	↓
High-Beta Power (23-35 Hz)	F4-C4, F4-T4, F4-P4, F4-O2	↓
Gamma Power (36-44 Hz)	F4-C4, F4-T4, F4-P4, F4-O2	↓

From Deeny *et al.*(35) results. *Coherence in expert shooters comparing to novices.

different locations on the scalp can display ERD and ERS simultaneously"(49). Under that perspective, Del Percio *et al.* (36), investigated the visuo-attentional and sensorimotor event-related desynchronization/synchronization of Theta, low- and high-Alpha, low- and high-Beta, and Gamma waves during pre-shot period (3 sec) in air pistol elite athletes and non-athletes in relation to performance. Low- and high-Alpha ERD in elite athletes were lower than in non-athletes over the whole scalp. Related to performance, among elite athletes the amplitude of event-related synchronization was larger for high score shots than for low score shots in right parietal and left central areas. They concluded that for expert shooters visuo-motor performance relates to a global decrease of cortical activity with increase of alpha and beta rhythms, corroborating previous studies(13).

Using those previous collected data(36), Del Percio *et al.*(37) proceeded further analyses to address the neural efficiency mechanism related to enhanced functional coupling. The objective was to observe cortico-cortical functional connectivity involved in visuo-spatial information and sensorimotor integration, including eye-hand coordination. To do so they compared spectral event related intra- and inter hemispheric coherence (F3: C3, T3, P3, O1; F4: C4, T4, P4, O2) in elite athletes' and non-athletes pistol shooters during the aiming period (three, two, and one sec before shot) in relation to the baseline period (five and four sec before shot). Table 4 presents a summary of the findings of Del Percio *et al.*(37). The authors concluded that intra- and inter-hemispheric coherence values in amplitude were stable in the elite athletes but not in the non-athletes. They discussed that, "according that experimental condition, the elite athletes exhibited neural efficiency related to stabilization of functional coupling in the sense of preparation of Alpha rhythms over parietal visuo-spatial cortex.

Table 4 – Significant results on intra- and inter-hemispheric event related coherence (ERCoh) in cortico-cortical regions in athletes and non-athletes pistol shooters

Waves	**Compared regions**	**ERCoh in elite athletes**
Intra-hemispheric amplitude		
Theta (4-6 Hz)	NS	-
Low-Alpha (8-10 Hz)	P3-T3, P4-T4, P3-O1, P4-O2	↑
High-Alpha (10-12 Hz)	P3-T3, P4-T4, P3-O1, P4-O2	↑
Low-Beta (14-22 Hz)	NS	-
High-Beta Power (23-35 Hz)	ME Group	↑
Gamma Power (36-44 Hz)	P3-T3, P4-T4	↑
Inter-hemispheric amplitude		
Theta (4-6 Hz)	NS	-
Low-Alpha (8-10 Hz)	P3-P4	↑
High-Alpha (10-12 Hz)	P3-P4	↑
Low-Beta (14-22 Hz)	NS	-
High-Beta Power (23-35 Hz)	ME Group	↑
Gamma Power (36-44 Hz)	ME Group	↑

From Del Percio *et al.*(37) results. **ERCoh**: event related coherence in cortico-cortical regions involved in task's attentional processes and visuo-motor behavior: comparison between elite athletes and non-athletes; **NS**: non-significant (p>0,05); **ME**: main effect (where there was no interaction).

Kim *et al.*(38) mapped brain activity through functional magnetic resonance imaging (fMRI) comparing elite, experts and novice archers at aiming period. The brain image results showed that in the elite group there was high activity in the cerebellar dentate indicating that "the cerebellum is involved in automating simultaneous movements" because promotes integration of the sensorimotor memory, which is enabled by high expertise for self-paced aiming tasks. Furthermore, at the crucial aiming moment, according to skill levels the authors found the following cortical activity differences: A) Elite archers showed higher activity at: supplementary motor area, temporoparietal area, and cerebellar dentate; b) Experts showed higher activity at: frontal superior area; and c) Novices showed higher activity at: superior and inferior frontal areas, ventral pre-frontal cortex, primary somatosensory cortex, primary motor cortex, and superior parietal lobule. Those findings corroborated the neural efficiency hypothesis since neural activity was more localized in elite and in experts than in novice archers. The authors theorized that systematic training on domain-specific cognitive and psychomotor abilities leads to neural efficiency. That explanation finds fulcrum in the literature: "skills developed in this way allow experts to perform with less cognitive effort than novices" (38,58,59).

Bertollo et. al.(39) examined Theta and Alpha ERS/ERD related to performance in pistol shooting. They found that ERS was mainly associated with optimal-automatic performance, in line with the neural efficiency hypothesis. They observed that more ERD related to optimal-controlled performance in neural adaptability conditions and skilled use of cortical resources. The authors explain that optimal performance can be typified by effort, attentional control, and use of resources of automatic performance. They adopted the idiosyncratic framework of the multi-action plan (MAP) model which proposes four performance types are: Type 1: Optimal-automatic; Type 2: Optimal-controlled; Type 3: Suboptimal-controlled; and Type 4: suboptimal-automatic. For more details, please read in the cited article(39) "The MAP model" section. Results showed that the four performance states pointed to unique psychophysiological states underlying performance. Therefore, the use of MAP model can present a framework that can be applied to develop strategies to improve shooting performance by using cognitive and neurofeedback techniques.

Di Fronso et.al.(40) in a case study examined in an Olympic athlete the Theta, Alpha (high and low) and Beta bands, aiming to identify the neural markers underlying optimal and sub optimal performance experiences of an elite air pistol shooter. Their findings exhibited that Alpha and Beta ERS patterns of cortical activity together with a minimum decrease of Alpha and Beta power indicate that good performance can be achieved when the athlete consciously set attentional focus to a core action component. Moreover, focusing attention on core components of action can improve performance even under distressful situations. The authors explain that this relates to skilled motor execution counteracting the unfavorable effects of voluntary control of execution processes. From a practical perspective, pre-performance routines allow the control of attentional resources prior to specific movement execution increasing Theta activity and modulating low and high Alpha activity, which can be done by using arousal, attention, and emotion regulation strategies(40). In that context, the neural efficiency can be observed.

There are some multi-sports modalities that involves shooting during physical effort. Gallicchio *et al*.(41) explored the influence of sub-maximal cardiovascular load on electroencephalographic activity preceding biathlon shooting and showed that higher frontal-midline Theta power, lower left-central Alpha power, and higher left-temporal Alpha power were associated with more accurate shooting, suggesting that monitoring processes are beneficial to shooting performance. Furthermore, among main results were that in expert biathletes the cardiovascular load did not change shooting performance.

Gong *et al*.(42) compared cortical activity in resting state with task execution in 35 trained shooters. The authors found significant linear correlation of shooting performance with coherence at Beta band between C3 and T3 sites. Results also showed correlation of length of the Theta band brain network in resting-state with shooting performance. Those findings pointed out potential neural mechanisms underlying successful shooting and indicate a new method to predict performance using EEG technique. In that context, Rogala *et al*.(60) pointed out that the resting-state EEG activity predicts improved attentional performance.

Woo & Kim(43) observed inter- and intrahemispheric coherences in young air pistol athletes in practice and competitive scenarios. Interhemispheric coherence in aiming period was higher in competition comparing to practice. Furthermore, they concluded that competitive anxiety may be related to reduced neural efficiency and cortical autonomy.

Gong *et al*.(44) examined the correlation of global and local EEG characteristics with shooting performance. They found that at the closest time window to the firing execution, there was a strong significant negative correlation of functional coupling of the right brain at Fp2, F4, and T4 sites at the low-Beta and high-Beta bands with performance. In that context, the lower the functional coupling, the higher the performance. The authors discussed that the prefrontal area is responsible for advanced planning and the right temporal lobe for visual-spatial function. In addition, they indicated that neurofeedback training can contribute to adjust these EEG characteristics to achieve better shooting performance.

Brain connectivity during aiming period (from three pre-shot sec) in shooting athletes was examined by Zhang *et al.*(45) comparing competitive and noncompetitive states. There was a linear correlation of Beta and Theta bands with performance at frontal, central, temporal, and occipital regions. Furthermore, at noncompetitive states, athletes presented Theta occipital power (O1, O2), Alpha power at frontal central (Fz) and left occipital (O3), together Beta power at frontal and mid-occipital (Oz) regions was higher at noncompetitive state. The authors concluded that competition increases cortical activity changing region's activation according to the individual.

In relation to efficacy, trainability and neuroplasticity that can be promoted by neurofeedback training in shooting sports, Gong *et al.*(46) examined the effects on non-expert pistol shooters (n=45). They stated three groups: sensory-motor rhythm group (C3, Cz, and C4); Alpha rhythm group (T3 and T4); and control group (no neurofeedback training). Main findings were that it was observed significant improvement in shooting performance of sensory-motor rhythm group (SMR). Concerning trainability, results showed that the degree of task difficulty in Alpha group was higher than in SMR group. Hence, the authors discussed that SMR feedback is preferred for training in non-expert shooters comparing to Alpha rhythm feedback training. In the study, it was also investigated if the neurofeedback training can lead to neuroplasticity. The authors examined the change in neural activity by resting EEG before and after the training period. In both training groups (Alpha and SMR), there was significant changes in resting cortical activity, which was considered as strong evidence of the neuroplasticity. Moreover, such neuroplasticity may explain the improvement on shooting performance.

Zhang *et al.*(47) compared functional brain connectivity between expert and novice rifle shooters during the pre-shot period through coherence analysis. In experts, the values of connection between P3 and C3 areas increased steadily during the pre-shot period. Moreover, there were fewer connections in left hemisphere networks in experts comparing to novices. The authors concluded that those results corroborate the neural efficiency hypothesis in experts.

The pre-shot period of air-pistol shooting is a crucial time during which the shooter must prepare for the ensuing shot release while is aiming and holding the pistol towards the target. Locating and maintaining the aim of the pistol requires the brain to process relevant visual information concerned with correct positioning of the pistol in relation to the target. Specifically, the shooter needs to achieve an optimal sight picture whereby the position of the foresight and rear sight of the pistol are correctly aligned in relation to the target(61). Expert archers and shooters have consistently demonstrated lower left hemisphere activation (predominantly over the anterior-temporal cortex of the brain), as inferred from increased Alpha power, during the final few seconds before shot release. Such reactivity of EEG Alpha power is indicative of an economy of cortical processing(27) and has been taken to reflect a reduction in verbal and analytic processes before shot release (20). Williams and Krane(62) characterized the ideal performance status in experts as a highly focused state with little mental effort. The functional relationships between low and high Alpha power among parietal, temporal, and occipital lobes were observed and compared between experienced air pistol shooters and beginner shooters(37).

Literature exhibits evidence that for best shooting performance there must be an increasing at Alpha power up to an ideal level prior to shooting, which is consistent with the thought that the experience gained throughout the practice can cause changes in the organization of the brain functions of experienced shooters or athletes' performance. Such findings are in line with Hatfield *et al.*(20) who suggested that increased Alpha activity was related to an increased accuracy. More recent studies have pointed out that the increasing in Alpha power should be accompanied of increasing in Beta power(26) at right hemisphere and Theta power at F3, F4 and Fz sites(32,41).

Summary of findings

The findings of this comprehensive systematic review study, from the results and discussion exhibited in the literature showed that cortical activity related to shooting task performance are the following:

Slow potentials (SP) (<1 Hz)

- Higher negative SP brain (increased cortical activity) relates to worst shots(22).
- At visual aiming shooters presented increasing in SP negativity, which related to poorer performance.
- Compared with novices, in marksmen there was a decreased tendency in negative SP preceding the trigger pull for better performance(23).
- Frontal (Fz) SP positivity at pre-shot period was associated with successful performance, but only if Oz was neutral, and SP at C4 was more negative than C3(25).
- For high-scoring shots there was increasing in SP positivity at pre-shot period at frontal central (Fz) and central (Cz) areas(25).

Theta waves (6-7 Hz)

- Marksmen presented significant more hemispheric Theta power than novices during the shooting task(27).

Theta power (6-7 Hz)

- At aiming period, experts showed significant increasing in Theta power at F3, F4, and Fz sites(32,41).

Alpha waves (low Alpha: 8-10 Hz; high Alpha 11-13 Hz)

- From 5.0 to 2.5 sec and 2.5 sec to pull trigger there were a decrease at Alpha waves frequency at the right brain, which continued up to pulling the trigger (20).
- From 3.0 to 0.5 sec at pre-shot time – Increasing in high-Alpha (12 Hz) waves activity in left hemisphere (T3, T4) relates to worst shots(21).
- Marksmen presented more low-Alpha (9 Hz) power at left temporal (T3), parietal ((P3), and occipital (O1), whereas there was no statistically significant difference at the homologous sites nor at F3, F4, C3, and C4 regions(27).
- At high-Alpha (10-11 Hz) waves, there was significant more power at right parietal (P4) site in marksmen than in novices(27).

Alpha power (8-12 Hz)

- Comparing to novices, elite rifle shooters present higher increasing in Alpha power at the left hemisphere and higher decreasing at the right hemisphere(28).
- Pistol learning processes (14 weeks) promoted increases: in Alpha power at left-temporal region (T3); and in event-related Alpha power at both temporal regions (T3, T4)(31).
- Before best shots, Alpha power increases at occipital central site (Oz)(29), visual attention to the pistol and target was progressively suppressed.
- Decreasing in Alpha power at occipital central site (Oz), from 2 sec before pulling the trigger, relates to worst shots(29), increasing aim-related visual information processing leads to decrease in performance.
- Excessive Alpha power in left hemisphere relates to poorer performance in shooting(21,26).

Beta power (18-22 Hz)

- Marksmen presented significant more Beta power hemispheric than novices, except at left-temporal (T3) region(27).
- Excessive increases in spectral Alpha power together with excessive increases in spectral Beta power relates to lower performance (worst shots)(26).

Gamma waves (36-44 Hz)

- At Gamma waves, marksmen exhibited less power than novices in all cortical regions(27).

Symmetry / Asymmetry

- Those findings indicated asymmetry between temporal areas (T3-T4) at Alpha band, which related to high performance in shooting (20).
- At Theta (6-7 Hz) waves, there were no differences in hemispheric asymmetry between marksmen and novices in shooting task(27).
- At low-Alpha (9 Hz) waves, marksmen presented lower asymmetry than novices at temporal region (T3, T4) (27).
- At high-Alpha (10-11 Hz) waves, marksmen presented lower asymmetry than novices at temporal region (T3, T4)(27).
- At Beta (18-22 Hz) waves, marksmen exhibited lower asymmetry than novices at C3, C4, T3, and T4 regions(27).
- At Gamma waves, marksmen presented lower asymmetry than novices at C3, C4, T3, and T4 sites(27).
- From the 1 sec pre-shot period, elite rifle shooters present increases in Alpha and Beta power at the left hemisphere and reduced levels of Alpha and Beta power changes higher than that observed in novices rifle shooters(28).

Coherence

There is lower coherence according to shooting expertise.

a)Marksmen compared to skilled shooters(30) presented lower coherence at:

- Low-Alpha band – between left temporal (T3) and midline frontal (Fz) regions.
- High-Alpha band – between left hemisphere (C3, P3, T3, O1) and Fz regions.
- Low-Beta band – between T3 and all midline regions (Fz, Cz, Pz).

b) In all examined epochs (four, three, two, one sec pre-shot period), expert shooters compared to novices(35) presented lower coherence at:

- Low-Alpha band – between F4 and T4 regions.
- High-Alpha band – between F3 and T3 regions.
- Low-Beta band – between F3 and T3 regions.
- High-Beta band – between F4,C4, T4, P4, and O2 regions.
- Gamma power – between F4, C4, T4, P4, and O2 regions.

Intra- and interhemispheric coherence related to shooting performance

- The amplitude in intra- and inter-hemispheric coherence were stable in the elite athletes but not in the non-athletes(37).
- . Interhemispheric coherence in aiming period was higher in competition comparing to practice(43).
- Competitive anxiety may be related to reduced neural efficiency and cortical autonomy(43).
- In experts, the values of connection between P3 and C3 areas increased steadily during the pre-shot period(47).
- During pre-shot period, there were fewer connections in left hemisphere networks in experts comparing to novices(47).

Synchronization/Desynchronization

- Low- and high-Alpha ERD in elite athletes were lower than in non-athletes over the whole scalp(36).
- Higher ERS amplitude relates to better shooting performance (36,39).
- Expert shooters present global decrease of cortical activity with increase of alpha and beta rhythms (ERS) related to better performance(36,40).

Mapping brain activity (EEG power) related to shooting performance

- Excessive increases in spectral Alpha power together with excessive increases in spectral Beta power relates to lower performance (worst shots)(26).
- Brain complexity (examined through nonlinear model) was lower in expert

shooters comparing to novices, and it was associated to performance(33).

- During aiming period, in experts the occipital gyrus and temporal gyrus were activated, whereas in novices, the frontal area was the main activated area(34).
- Elite archers showed higher activity at: supplementary motor area, temporoparietal area, and cerebellar dentate(38).
- Experts showed higher activity at: frontal superior area (38).
- Novices showed higher activity at: superior and inferior frontal areas, ventral pre-frontal cortex, primary somatosensory cortex, primary motor cortex, and superior parietal lobule (38).
- High Theta power at Fz together with lower Alpha power at C3, and higher Alpha power at T3 sites. Alpha power was associated with shooting performance (41).
- Coupling of the right brain – Fp2, F4, and T4 areas at the low-Beta and high-Beta bands related to performance: the lower the functional coupling, the higher the performance (44).
- Alpha power at frontal central (Fz) and left occipital (O3), together Beta power at frontal and mid-occipital (Oz) regions was higher at noncompetitive state comparing with competitive state(45).
- Competition increases cortical activity changing region's activation according to the individual(45).

Resting EEG state (baseline pre-task)

Literature showed that resting state (baseline pre-task EEG) relates to shooting performance:

- There was positive correlation of Beta band coherence between C3 and T3 sites related to shooting performance(42).
- Theta band brain network at resting-state related to shooting performance(42).
- Resting EEG state examine showed evidence of neuroplasticity induced by neurofeedback training, which related to performance(46).

Strengths and limitations of the study

One strong point of the study was the focus set on shooting sports (pistol, rifle, and archery) which differs from other modalities such as basketball and/or golf. The strategy adds specific knowledge contributing to clarify brain functioning during that complex visuo-cognitive-psychomotor task.

The limitation refers to the review study method that can be affected by the absence of publications of studies that did not find association among study variables. Nevertheless, we tried to produce highly comprehensive research on the issue without time limitation, intending to present the utmost and complete review as possible.

Conclusion

We sought to review the research focusing on the neural efficiency concept related to shooting sports' performance. The findings showed expert shooters at aiming period and pulling the trigger moment there was an increase in Alpha activity at the left temporal (T3) region and stability in the right temporal lobe (T4). Moreover, in experts there is a general lower cortex activity of the anterior-temporal cortex.

The results of the present study support a reduction in cognitive processing by specialists during the aiming period of target sports such as pistol shooting. Furthermore, left hemisphere increased Alpha power was associated with best shooting performance. Studies investigated from six to one second prior to execution of the shot (pulling the trigger) and the highest levels of Alpha power were found in the 2 seconds immediately before execution for the best shots but decreased during worst shots. Better shooting performance in relation to brain activity is characterized by the stabilization of functional coupling of preparatory EEG rhythms between visual-spatial parietal area and other posterior cortical areas. In that context, literature is consistent supporting the neural efficiency of brain function related to the effects of sensory motor training on high-performance, which indicates that motor cortex activity decreased, while there is an increase in task performance after a training period. Increased Alpha power in the left hemisphere suggests that there is less brain activity related to analytical attention and visual attention on the target.

The findings present in literature showed that shooters reduced their attention to external visual stimuli (i.e., pistol or sight picture) during the pre-shooting period of the best shots while increasing visual attention during the pre-shot period of the worst shots, suggesting that best shots occurred when they did not have maximum visual attention at the target location. The shooting technic refers to focusing attention on the aiming not in the target. Therefore, fewer eyes movement are expected before a good shot, consequently, lower occipital brain activity. That can be explained because experienced shooters achieve high motor expertise through the acquisition of autonomous motor control mechanisms, allowing the execution of the shot to be performed with a cognitive processing efficiency requiring less energy expenditure.

Expert shooters can reduce pre-triggered visual attention by relaxing their visual focus and reducing their concentration on the sight picture. In contrast, an absence of such visual suppression through a maintenance or increase in concentration on the sight picture can potentially interfere with automatic control of the focus of attention by blocking a likely shift in attentional focus at the time of shooting, resulting in decreased performance. There is the suppression of cortical process not related to vision during the pre-shot in target sports and found effect greater Alpha power the EEG to the left than right local anterior temporal, demonstrating reduction in verbal analytic processes. Thus, according to the inference that the Alpha power of the EEG at the left antero-temporal site reflects the amount of verbal and analytical processing, and these results demonstrate a complex relationship between pre-shot cognition and subsequent shooting performance showing that the expert shooters exhibit greater left temporal Alpha power during the pre-shot period than the novice shooters, however, it seems that a very large increase in that Alpha power can lead to decreases in performance. Thus, there may be an optimal cognitive processing zone in the left temporal cortex for specialists with a very low or very high power associated with final results.

More recent studies examined coherence and Alpha, Beta and Theta waves differences between novice and expert shooters, and literature is consistent that the higher the expertise the better energy economy can be observe for cortical activities at different brain regions. In summary, literature shows that relationships of brain activity and intelligence with performance are consistent on performance tasks. For expert shooters visuo-motor performance relates to a global decrease of cortical activity with increase of alpha and beta rhythms. Several factors will determine whether the cortical activation increase or decrease in a given area, according to the task complexity, because expertise relates to less brain cortical activation in performance tasks. In that context, the hemispheric laterality in marksmen implies that they present high attentional focus degree. Thus, they are capable to reduce left cerebrum conscious mental activity, reducing, consequently, potential distracting cognitions.

Finally, results of the present review study showed that the hypothesis of neural efficiency is applicable in target shooting sports as pistol, rifle, and archery.

As the neural efficiency hypothesis is gaining consistency through the development of the knowledge, further studies should examine Alpha band together with Betha and Theta bands at F3, F4, Fz, T3, T4, T5, T6, and O1, O2, Oz regions to additional examine and better understanding of brain mechanisms related to performance in visuomotor task with high demand of attentional focus.

Conflict of interests

There is no conflict of interest in this study.

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