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RESEARCH PROGRESS ON THE COMBINED APPLICATION OF TDCS AND COGNITIVE RELATED TASKS IN THE FIELD OF SPORTS AND EXERCISE

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Abstract : *With the rapid development of non-invasive brain stimulation methods as an outcome of neuroscience, transcranial direct current stimulation (tDCS) has emerged as a non-invasive neuromodulation technique that modulates cortical excitability and enhances neuroplasticity, demonstrating potential for improving higher-order cognitive and motor functions closely associated with sports performance, including attention, executive function, motor learning, and decision-making. This review systematically examines research trends in the combined application of tDCS and Cognitive-related Tasks in the field of sports and exercise, analyzes the theoretical foundations and physiological mechanisms, diagnoses current status and limitations, and proposes future research directions. Analysis results confirm that combined interventions exhibit amplified effects in specific domains such as executive function, motor skill acquisition speed, and skill retention compared to tDCS application alone. However, several challenges remain to be addressed, including the absence of optimized stimulation parameters (location, intensity, synchronization), limitations in accounting for individual differences, ecological validity concerns regarding laboratory environments, insufficient evidence for long-term effects and safety, and sports ethics issues. In conclusion, although the combined approach of tDCS and Cognitive-related Tasks represents a promising paradigm for enhancing sports and exercise performance, future research should focus on developing optimized and personalized protocols, strengthening field applicability, verifying long-term effects and safety, elucidating neurophysiological mechanisms, and establishing ethical standards.*

1. Introduction

In recent years, as the reserves of physical and technical potential derived from traditional training methods of previous eras have progressively diminished, sports cognitive training applying neuroscience achievements has emerged as an important methodology for enabling athletes to overcome psychological limitations.

One such outcome of neuroscience is non-invasive brain stimulation technology, particularly transcranial direct current stimulation (tDCS). tDCS is a technique that applies weak direct current to specific brain regions through electrodes attached to the scalp, modulating neuronal membrane potentials at subthreshold levels. Anodal tDCS primarily increases cortical excitability, while cathodal tDCS decreases it, ultimately altering synaptic plasticity and neural network function. Numerous prior studies reported in PubMed have demonstrated that tDCS can improve attention, working memory, executive function, and motor skill acquisition speed. For instance, a meta-analysis by Dedoncker et al. (2016) reported that anodal tDCS over the left dorsolateral prefrontal cortex (DLPFC) significantly improves cognitive functions including episodic memory. Furthermore, evidence has accumulated indicating that tDCS targeting the primary motor cortex (M1) facilitates motor learning and skill acquisition (Stagg & Nitsche, 2011).

Meanwhile, Cognitive-related Tasks refer to training programs designed to strengthen targeted cognitive functions (attention, visuospatial processing ability, etc.). In sports, these have been applied in various forms such as visual attention training, motor imagery training, multitask training, and motor skill learning. Attempts to combine tDCS with Cognitive-related Tasks are based on the hypothesis that the two interventions can exert complementary effects. Specifically, tDCS may optimize the brain's preparatory state and lower the threshold for neuroplasticity, thereby amplifying and consolidating neural changes and learning processes induced by cognitive task performance. Fritsch et al. (2010) suggested that tDCS promotes brain-derived neurotrophic factor (BDNF)-mediated synaptic plasticity, and motor learning can be enhanced when this effect is combined with concurrent neural activity (e.g., training).

Therefore, the purpose of this review is to systematically synthesize recent experimental evidence on the combined application of tDCS and Cognitive-related Tasks in the sports and exercise domain, examine its theoretical basis and physiological mechanisms, identify limitations in current research, and suggest future research directions. Through this, we aim to provide comprehensive guidance on how the combined approach of tDCS and Cognitive-related Tasks may contribute to enhancing athletic performance and health-related exercise.

2. Theoretical Basis and Physiological Mechanisms of Combined tDCS and Cognitive Task Application

The combined application of tDCS and Cognitive-related Tasks is grounded in the theoretical assumption that the two interventions are complementary and can produce synergistic effects. This approach, which aims to promote neuroplasticity and optimize cognitive-motor learning processes, has garnered attention in sports science. This chapter systematically examines the theoretical foundations and supporting neurophysiological mechanisms of this combined approach.

2.1 Theoretical Basis

The combined application of tDCS and Cognitive-related Tasks can be explained from two major theoretical perspectives. The first relates to learning facilitation through enhanced neuroplasticity, and the second concerns improved efficiency of cognitive-motor integration processing.

Learning Facilitation through Enhanced Neuroplasticity

tDCS modulates the membrane potentials of neurons in specific brain regions at subthreshold levels using weak direct current. Anodal tDCS primarily induces neuronal depolarization, increasing cortical excitability, while cathodal tDCS induces hyperpolarization, decreasing excitability. These excitability changes are not merely transient but can induce phenomena similar to long-term potentiation (LTP) and long-term depression (LTD), which form the basis of synaptic plasticity.

Prior research by Fritsch et al. (2010) suggested that tDCS promotes BDNF-mediated synaptic plasticity, and motor learning can be enhanced when this effect is combined with concurrent neural activity (e.g., cognitive training). That is, applying tDCS during cognitive training may more effectively strengthen synaptic connections in specific neural circuits activated by training, thereby increasing learning speed and efficiency.

As emphasized in Lars Lienhard's book *"Training Begins in the Brain,"* the limits of motor performance are determined by the actions of the brain and nervous system, not the muscular system. Therefore, a combined approach that enhances cortical neuroplasticity via tDCS while simultaneously and repeatedly activating specific neural circuits through cognitive training represents a theoretically valid strategy for promoting the 'neural circuit optimization' that is central to motor learning.

Improvement of Cognitive-Motor Integration Processing Efficiency

Optimal motor performance is achieved through a continuous process involving high-quality sensory input, efficient central processing, and precise motor output. tDCS possesses the potential to directly modulate the function of brain regions responsible for central processing (e.g., DLPFC), including attention, working memory, and executive functions.

Conversely, cognitive training (e.g., visual attention training, motor imagery training) or cognitive-motor integration training (e.g., observational learning, virtual reality games) improves the efficiency of these processing systems through practice (Hill AT. et al.). Thus, when tDCS optimizes the brain's 'preparatory state,' the neural changes and learning processes induced by cognitive training can be amplified and consolidated. This implies that combining neural training that enhances sensory input quality with tDCS that improves central processing efficiency can yield mutually complementary effects.

As argued in *"The Athletic Brain: How Neuroscience is Revolutionising Sport and Can Help You Perform Better,"* improving athletic ability requires the integration of brain training, not just muscle training. The combination of tDCS and cognitive training concretizes this argument as an attempt to directly optimize brain function away from muscle-focused training. Particularly, decision-making and multitasking abilities demanded in complex sports situations are closely related to the function of regions like the DLPFC, and tDCS can contribute to enhancing these higher-order cognitive abilities.

2.2 Neurophysiological Mechanisms

The theoretical validity of the combined application of tDCS and cognitive training is supported by specific neurophysiological mechanisms, which can be explained at neuronal, synaptic, and neural network levels.

Enhancement of Neuronal and Synaptic Plasticity

tDCS alters the baseline excitability of neurons in the targeted region. When tDCS is applied during cognitive training (the 'on-line' approach), the state of increased excitability established by tDCS directly influences the precise neuronal populations activated by the training, potentially enhancing the connection strength of those synapses. LTP-like phenomena mediated by the glutamate system are known to play a significant role in this process. The after-effects of tDCS extend beyond simple excitability changes, persisting long-term through these synaptic plasticity mechanisms. Thus, while cognitive training induces learning, tDCS plays a role in consolidating the consequent neural changes (Fritsch B et al.).

Improvement of Neural Circuit and Network Efficiency

Cognitive training activates brain neural networks associated with specific Cognitive-related Tasks (e.g., attention network, executive function network). When tDCS intervenes in this process, it can increase the signal-to-noise ratio of information transmission within that network. That is, it enhances relevant signals while suppressing interfering signals, improving the overall information processing efficiency of the network (Polanía R et al.).

Research indicates that following combined cognitive training and tDCS, functional connectivity between the left DLPFC—a core region for working memory and executive function—and its contralateral homotopic area was significantly strengthened. This demonstrates that combined intervention induces greater changes at the distributed brain network level, beyond mere activation of a single region. Stagg & Nitsche (2011) provided the physiological basis explaining these network-level changes, suggesting that tDCS effects alter neural plasticity through mechanisms similar to LTP/LTD.

In conclusion, the combined intervention of tDCS and Cognitive-related Tasks directly engages the biological processes of brain learning (neuroplasticity), eliciting complementary effects. Consequently, it is establishing itself as a promising paradigm enabling faster, stronger, and more enduring improvements in cognitive and motor abilities compared to single interventions alone.

3. Characteristics and Current Status of Research on Combined tDCS and Cognitive Task Application in Sports and Exercise

In recent years, with the active introduction of neuroscience research findings into the sports and exercise domain, numerous studies have been conducted applying traditional training methods in combination with new electrical stimulation techniques to improve limitations in cognitive-related abilities.

To outline the research status of the combined application of cognitive-related tasks and tDCS in sports over the past decade (2014-2025), relevant literature was retrieved from academic databases including CNKI, PubMed, Web of Science, and EBSCOhost using keywords such as "sports," "transcranial direct current stimulation," "tDCS," "cognitive," and "combined with." Fifteen studies were identified that combined tDCS with cognitive-related tasks, targeting either professional athletes or healthy populations. Based on the final selection of research literature, a total of 15 studies were identified that combined tDCS with Cognitive-related Tasks in the sports and exercise domain, targeting either professional athletes or healthy individuals.

To elucidate the main characteristics and current status of research related to the combined application of Cognitive-related Tasks and tDCS, key items including researcher, subjects, training combined with tDCS, application area, synchrony, experimental group design, stimulation parameters (site, intensity, duration, electrode size), tDCS application period and frequency, effectiveness (effective/ineffective), and final conclusions were selected. The characteristics of the research topics are presented in the following table.

Table 1. Item-specific Characteristics of Empirical Studies on Combined Application of Cognitive-related Tasks and tDCS in Sports and Exercise

No.	Researchers (Year)	Subjects	Combined Task Type	Application Area	Synchrony	Experimental Groups	Stimulation Parameters	Application Period/Frequency	Effectiveness	Final Conclusion
1	Pan Shanchao (2024)	Tennis athletes	Mindfulness training	Attention, Executive function	Off-line	3 groups (Mindfulness, tDCS, Combined)	F3 (Left DLPFC), 2mA, 20 min, 1 cm²	8 weeks, 4 times	**Effective:** Executive control/function **Ineffective:** Attentional alertness	Combined intervention most effective for executive function; long-term effects confirmed
2	Bai Zitong (2023)	Athletes	Mindfulness training	Attention, Motor-cognitive performance	Off-line	4 groups (Control, Mindfulness, tDCS, Combined)	F4/P4 (Right DLPFC/Parietal), 2mA, 20 min, 1 cm²	Single session, 1 time	**Effective:** Executive control network, HRV **Ineffective:** Alerting/Orienting networks	Combined approach valuable for enhancing executive control
3	Hou Guozheng (2023)	Healthy adults	Motor imagery	Working memory, Upper limb motor skill learning	On-line	3 groups (Sham, tDCS, Combined)	F3 (Left prefrontal), 2mA, 20 min, 2 cm²	15 days, 8 times	**Effective:** Working memory, throwing accuracy, delayed memory **Ineffective:** Total cognitive assessment score	tDCS combination improves motor skill learning efficiency and partially enhances cognition
4	Saruco et al. (2018)	Healthy adults	Motor imagery	Balance and postural control	On-line, Off-line	3 groups (Sham/Active stimulation before/during motor imagery)	Cz, 1mA, 10 min, 25 cm²	Single session, 1 time	**Effective:** Postural control improved with stimulation DURING motor imagery **Ineffective:** Stimulation BEFORE motor imagery	tDCS most effective when applied synchronously with motor imagery
5	Martin et al. (2014)	Healthy adults	Working memory task	Working memory	On-line, Off-line	2 conditions (On-line/Off-line)	F3 (Left DLPFC), 2mA, 30 min, 35 cm²	Single session, 1 time (1-month interval)	**Effective:** On-line stimulation enhanced skill acquisition **Ineffective:** Off-line stimulation no accuracy improvement	On-line (synchronous) stimulation more beneficial for learning and neuroplasticity
6	Oldrati et al. (2017)	Healthy adults	Customized visuosp	Visuospatial ability	On-line,	3 groups (On-line,	F3 (Left DLPFC), 1.5mA, 20	Single session, 1 time	**Effective:** On-line group improved in	On-line tDCS more

			atial training		Off-line	Off-line, Sham + training)	min, 25 cm²		complex tasks and transfer effects **Ineffective:** Off-line and sham groups no difference	effective in enhancing spatial training effects
7	Moreira et al. (2022)	Basketball athletes	Inhibitory control task	Cognitive performance, Shooting accuracy	On-line	3 groups (tDCS, Sham, Control)	F3 (Left DLPFC), 2mA, 20 min, 25 cm²	Single session, 1 time	**Effective:** None **Ineffective:** No additional benefit in cognitive tasks or shooting performance	Left DLPFC tDCS did not confer additional cognitive/motor benefits in professional athletes
8	Neto et al. (2021)	Amateur soccer players	Visuomotor training	Choice reaction time, Cognitive function	On-line	2 groups (tDCS, Sham)	F3 (Left DLPFC), 2mA, 20 min, 35 cm²	5 days, daily	**Effective:** Shortened reaction time in specific muscles of trained/untrained limbs **Ineffective:** Other muscle reaction times, cognitive function	Combined tDCS effectively shortens specific muscle reaction times
9	Zhao Yunbo (2022)	Skilled sprinters	Observational learning	Sprint start technique learning	On-line	4 groups (Observation, tDCS, Combined, Control)	FCz (SMA), 2mA, 15 min, 0.8 cm²	4 days, daily	**Effective:** Combined group reduced reaction/movement/response times; effects sustained **Ineffective:** tDCS alone group no improvement in movement time	Combined intervention most effective for start skill learning with lasting effects
10	Mangat et al. (2025)	Healthy adults	Golf putting skill learning	Long-term memory retention of motor skills	Off-line	3 groups (Anodal tDCS, Cathodal tDCS, Sham)	M1, 1mA, 20 min	2 days, 2 times	**Effective:** Cathodal tDCS group better long-term memory and learning stability **Ineffective:** No differences in skill acquisition or transfer	Pre-training cathodal stimulation of M1 beneficial for enhancing long-term memory
11	Shahbazi et al. (2024)	Healthy adolescents	Virtual reality sports games	Motor coordination	Off-line	3 groups (Combined, Sham, VR control)	Cz (M1) & F3 (Left DLPFC), 2mA, 20 min, 20 cm²	4 weeks, 12 times	**Effective:** Combined group sustained coordination improvement	Repeated tDCS application can enhance and maintain VR

										training effects
12	Meek et al. (2021)	Healthy adults	Dart throwing skill learning	Motor skill learning speed	On-line	3 groups (Anodal tDCS, Cathodal tDCS, Sham)	M1, 2mA, 20 min, 35 cm²	Single session, 1 time	**Effective:** Anodal tDCS accelerated learning **Ineffective:** Cathodal tDCS and Sham no difference	M1 anodal tDCS facilitates on-line learning speed of complex motor skills
13	Perez et al. (2025)	Healthy adults	Variable-target dart task	Motor adaptation	On-line	2 groups (Anodal tDCS, Sham)	M1, 2mA, 20 min	Single session, 1 time	**Ineffective:** Anodal tDCS failed to additionally facilitate learning	Under varying conditions, M1 tDCS ineffective for accelerating learning
14	Guo et al. (2024)	Healthy adults	Sequential visual isometric pinch force task	Finger fine motor skill acquisition	On-line, Off-line	3 groups (On-line, Off-line, Sham)	C3/CP3 (Left M1), 1.5mA, 20 min	3 days, daily	**Effective:** Skill acquisition increased in both On-line & Off-line groups; On-line efficiency superior	On-line HD-tDCS more effective for motor skill acquisition and brain processing efficiency
15	Pantovic et al. (2023)	Healthy adults	Complex overhand throwing task	Complex motor skill learning	On-line	2 groups (tDCS, Sham)	Left M1, 1.5mA, 5/20 min, 35 cm²	3 days, twice daily	**Effective:** tDCS group increased total learning and M1 excitability **Ineffective:** Learning improvement not directly correlated with excitability increase	Repeated M1 tDCS facilitates complex whole-body motor skill learning

3.1 Basic Study Design Aspects

The study design and methodology section includes items related to research subjects, application areas, synchrony, and experimental group design.

Research Subjects and Application Areas

Three studies targeted professional athletes, while 12 studies involved healthy adults, indicating that research in the health and exercise domain occupies a relatively larger proportion compared to the professional sports domain. This suggests that research on combined tDCS and cognitive task application in professional sports remains in its early stages, with foundational studies primarily focused on the health and exercise domain.

Studies targeting professional athletes mainly focused on sport-specific cognitive functions (attention, inhibitory control), choice reaction time, and cognitive function improvement. In contrast, studies on healthy adults aimed to enhance general cognitive and motor functions such as basic motor skill acquisition, coordination, and memory.

Furthermore, these studies demonstrate that the combined application of tDCS and Cognitive-related Tasks in the sports and exercise domain is expanding beyond simple cognitive function enhancement into areas directly linked to sports performance—cognitive-motor abilities—although this remains at an early stage. Particularly in professional sports science, methods for improving attention, a core element of athletic performance, are receiving significant attention, with initial experimental evidence regarding their effectiveness accumulating.

Synchrony

Seven studies employed an **on-line** approach (applying tDCS simultaneously with cognitive or motor skill acquisition tasks), while five studies used an **off-line** approach (applying tDCS separately before or after training). Greater research focus is being placed on on-line approaches that utilize temporal coincidence of neuroplasticity to directly strengthen neural circuits activated during learning.

Notably, studies by Saruco et al. (2018), Martin et al. (2014), Oldrati et al. (2017), and Guo et al. (2024) conducted comparative analyses between on-line and off-line approaches, consistently finding that on-line stimulation was more effective than off-line stimulation in terms of learning and neuroplasticity.

The on-line approach has the theoretical advantage of enabling tDCS to directly amplify brain plasticity occurring during training, whereas the off-line approach aims for post-training consolidation or pre-training preparatory effects.

The effectiveness of on-line stimulation is explained by temporal coincidence of neuroplasticity. Performing cognitive or motor tasks while tDCS modulates brain excitability activates specific neural circuits, allowing tDCS effects to be selectively reinforced within those circuits. According to Fritsch et al. (2010), synaptic plasticity (LTP/LTD) is cooperatively enhanced when tDCS and neural activity occur simultaneously. Conversely, off-line stimulation appears to exert effects indirectly by modulating the plastic state induced by training or influencing its consolidation (Mangat et al., 2025). Depending on the specific task, such as balance ability in Saruco et al. (2018), the off-line approach may be more suitable.

Experimental Group Design

To isolate pure effects and statistically examine interactions between them, experiments were designed with various group divisions from the outset.

Most studies adopted randomized controlled trial designs, striving for methodological rigor. Experimental groups typically consisted of tDCS alone, cognitive/motor training alone, tDCS+task combined group, and sham-tDCS control group.

The use of sham-tDCS in the vast majority of studies enabled clearer identification of specific tDCS effects. Conversely, some studies that did not include a sham group (Pan Shanchao, 2024; Zhao Yunbo, 2022) may have limitations in demonstrating the pure additive benefits of tDCS beyond training effects. This underscores the importance of international standard double-blind, placebo-controlled experimental designs as an essential element for enhancing research reliability.

For instance, studies by Pan Shanchao (2024) and Bai Zitong (2023) included groups with cognitive training alone or Cognitive-related Tasks combined with sham-tDCS stimulation, conducting comparative analyses with the combined group to investigate the extent of additional effectiveness in the combined condition.

Such experimental group designs allowed these studies to draw nuanced conclusions—for example, that mindfulness training alone has significant effects even without tDCS, but combining tDCS produces additional amplification effects in executive control function. This demonstrates methodological maturity in investigating the complex relationship between tDCS and cognitive abilities.

3.2 Intervention Protocol Aspects

The intervention protocol section includes the Cognitive-related Tasks combined with tDCS, tDCS stimulation parameters (site, intensity, duration), and application period/frequency.

Training Tasks Combined with tDCS

Training tasks combined with tDCS in empirical studies can be broadly categorized into pure cognitive tasks and motor skill learning tasks with cognitive components.

Studies combining with pure cognitive tasks focused on mindfulness training, motor imagery, working memory tasks, attentional function, and visuospatial ability training. Studies combining with motor skill learning tasks containing cognitive elements concentrated on visuomotor training, observational learning, virtual reality sports games, and motor skill learning such as dart throwing.

Stimulation Parameters

- **Stimulation Site:** In tDCS studies combined with pure cognitive functions, the left dorsolateral prefrontal cortex (L-DLPFC, F3)—associated with attention, working memory, and executive function—was most frequently used. In tDCS studies combined with motor skill learning, the primary motor cortex (M1, C3/Cz/FCz) was predominantly targeted.
- **Stimulation Intensity:** Most studies used **2mA**. Some studies (Saruco et al., 2018; Mangat et al., 2025) applied **1mA**, while others (Oldrati et al., 2017; Guo et al., 2024; Pantovic et al., 2023) applied **1.5mA**.
- **Stimulation Duration:** Nearly all studies applied tDCS for **20 minutes**, making this the most common duration.
- **Electrode Size:** Considerable variation was observed. **35cm²** was relatively common. Apart from high-definition (HD) tDCS studies (Guo et al., 2024), some studies used small-area electrodes of **1-2 cm²** (Pan Shanchao, 2024; Bai Zitong, 2023; Hou Guozheng, 2023; Zhao Yunbo, 2022).

Differences in stimulation sites are attributable to **task specificity**. The DLPFC is closely associated with higher-order cognitive processing, while M1 is linked to motor execution and learning. The relatively consistent pattern of stimulation intensity and duration suggests that the 2mA/20min parameter is currently the most widely accepted in terms of safety and efficacy (Bikson et al., 2016). The diversity in electrode size reflects debates concerning focality and current density. Small-area electrodes can selectively stimulate specific regions with higher current density but may increase discomfort. The impact of area differences on effect sizes has not been clearly established and remains an actively researched topic.

Application Period and Frequency

Eight studies employed single-session applications, while seven studies used repeated session applications.

Single-session studies primarily focused on immediate effects and mechanism exploration, whereas repeated-session studies aimed more at evaluating cumulative effects, long-term retention of learning, and practical feasibility as a training protocol. The study by Shahbazi et al. (2024) indicated that 12 sessions of repeated stimulation produced greater improvements in motor coordination compared to previous studies using 1-4 sessions, emphasizing the importance of repeated application. This suggests that behavioral changes may clearly manifest only after neuroplastic changes accumulate, consistent with Monte-Silva et al. (2013), who proposed that multiple-session protocols may be necessary for long-term tDCS effects.

3.3 Effectiveness and Conclusions

- **Effectiveness:** The majority of the 16 analyzed studies reported additional benefits of combined tDCS and cognitive-motor task application in specific domains compared to single interventions alone. Positive effects were particularly prominent in executive function (Pan Shanchao, 2024; Bai Zitong, 2023), working memory (Hou Guozheng, 2023; Martin et al., 2014), motor skill learning speed and accuracy (Hou Guozheng, 2023; Neto et al., 2021; Zhao Yunbo, 2022; Meek et al., 2021; Guo et al., 2024; Pantovic et al., 2023), and long-term memory of skills (Mangat et al., 2025).
- **Ineffectiveness:** However, some studies (Moreira et al., 2022; Perez et al., 2025) or specific outcome measures within studies (attentional alertness in Pan Shanchao, 2024; specific muscle group reaction times and cognitive function in Neto et al., 2021) did not show significant additional effects of tDCS.

Differences in effectiveness may be attributable to the following factors:

- **Subject Characteristics:** Professional athletes (Moreira et al., 2022) may already possess near-ceiling levels of cognitive and motor abilities, leaving limited room for additional improvement via tDCS ('ceiling effect'). Research by Reis et al. (2009) suggested that the stimulatory effects of tDCS may be related to motor proficiency.
- **Task Complexity and Characteristics:** Tasks with continuously changing targets (Perez et al., 2025) may be less amenable to tDCS effects compared to tasks in stable environments (Meek et al., 2021). Applying tDCS before motor imagery has been reported to potentially produce adverse effects (Saruco et al., 2018), demonstrating the importance of **task-stimulation sequence**.

- **Individual Differences:** Pantovic et al. (2023) found no correlation between tDCS-induced increases in M1 excitability (MEP) and the degree of motor learning improvement, suggesting the existence of individual variability in response. This aligns with international research findings (Vergallito A et al., 2022) indicating that genetic background, anatomical differences, and initial brain state may influence tDCS responsiveness.

4. Reflections on Combined tDCS and Cognitive Task Application in Sports and Exercise

While the combined application of tDCS and Cognitive-related Tasks in the sports and exercise domain demonstrates promising potential, synthesizing prior research reveals several shortcomings in methodological and practical aspects. Objective recognition of these limitations will contribute to setting future research directions and enhancing the practical utility of this approach.

4.1 Lack of Standardization in Stimulation Parameters and Application Protocols

Non-Systematic Selection of Stimulation Parameters

Stimulation parameters related to tDCS application refer to stimulation site, intensity, and duration. In other words, this concerns the question of how to combine stimulation site, intensity, and duration to achieve optimal effects.

Although prior studies predominantly selected the left DLPFC or M1 as stimulation sites, clear justifications for how these selections optimally relate to the characteristics of the research task were often not provided. As analyzed in previous studies, these stimulation parameters differ according to research tasks. The problem lies in the fact that the rationales for determining and applying stimulation parameters for specific research tasks vary or remain unclear.

Stimulation intensity (1-2mA) and duration (10-20 minutes) also largely follow conventional practices from existing literature. Systematic approaches based on optimal dose-response relationships required for specific cognitive-motor tasks represent areas requiring further research depth. As mentioned in the theoretical basis of combined application, the effects vary depending on which brain region is stimulated, at what intensity, and for what duration. Therefore, establishing standards related to stimulation parameters and conducting research with clear justification according to such standards would enhance objectivity.

Insufficient Research on Effects Related to Synchronization Experimental Design

Clear empirical evidence regarding the differential effects of synchronization timing between cognitive task performance and tDCS (On-line: stimulation during training; Off-line: stimulation before/after training) is lacking. While Mangat B et al. (2025) demonstrated that Off-line application of cathodal stimulation to M1 *before* training was effective for enhancing long-term memory, many studies (e.g., Zhao Yunbo, 2022) have conversely adopted On-line approaches. Although Fritsch B et al. (2010) support the theoretical validity of the On-line approach, optimal synchronization strategies may vary depending on task type and goals, and systematic comparative research on this remains insufficient.

Inconsistency in Application Period and Frequency

The optimal period and frequency for combined tDCS and cognitive training application vary considerably depending on research objectives, subjects, and targeted cognitive domains. Generally, since tDCS stimulation aims to induce lasting changes through brain plasticity, systematic and repeated application over a certain period is important.

Continuous stimulation and repeated training are necessary to strengthen synaptic connections and induce long-term changes in brain network efficiency. However, differences in experimental period settings and application frequencies result in insufficient evidence regarding the most reasonable duration. Application periods and frequencies vary widely, ranging from single-session studies to long-term studies exceeding 8 weeks, leading to insufficient evidence regarding the minimum/optimal exposure required for sustained improvement in cognitive-motor functions. While Shahbazi N et al. (2024) demonstrated that 4 weeks of repeated application maintained delayed effects, whether such long-term protocols are universally applicable across all cognitive-motor domains remains unverified.

Importantly, almost none of the studies mentioned the issue of application timing. Accurately determining application timing is crucial when introducing researched methods into practical implementation. As is well known, neural process variability exhibits certain differences according to human biological rhythms. Therefore, accurately determining application timing for both tDCS brain stimulation and cognitive training emerges as an important issue. If effectiveness assessments were conducted at times when neural process variability is completely different, and differences were comparatively analyzed to determine effectiveness, this would not constitute an accurate evaluation. Similarly, research on combined tDCS and cognitive training should be conducted with appropriately selected application timing.

4.2 Absence of Personalized Research

Despite evidence that tDCS effects may show marked differences according to individual brain structure/function, genetic background, training status, and sport-specific characteristics, personalized studies accounting for these factors have rarely been conducted.

Limitations in Reflecting Sport-Specific Characteristics

Existing research has primarily focused on general cognitive functions (working memory, executive function) or basic motor skills (putting, arm reaching). Studies directly addressing cognitive-motor tasks unique to specific sports such as soccer or tennis (e.g., predictive decision-making in soccer, rapid response selection in tennis) are relatively scarce. Given that cognitive abilities themselves must substantially reflect sport-specific characteristics, and from a practical perspective, research should be conducted on cognitive ability development according to specific sports and their technical levels.

Weak Consideration of Individual Difference Factors

Although it has been suggested that individual baseline brain excitability, BDNF genotype, sex, and training history may influence tDCS responsiveness, most studies have neither controlled for nor analyzed these variables. This constitutes a major cause of inconsistency in effects between studies and among individuals, despite identical protocols. Research seeking personalized optimal strategies beyond result generalization is necessary.

Therefore, rather than seeking a single method universally applicable to all athletes, developing personalized tDCS stimulation methods combined with individual athletes' neurophysiological characteristics, sports type, and required Cognitive-related Tasks would likely be more effective.

4.3 Limitations of Laboratory Environment and Field Applicability Issues

The verification of combined tDCS intervention effects has been excessively dependent on controlled laboratory environments, raising questions about whether results can effectively transfer to the complex demands of actual sports settings.

Lack of Ecological Validity

Most studies used simplified Cognitive-related Tasks or isolated motor skills as assessment indicators. For example, Neto EM et al. (2021) measured choice reaction time, but it is unclear how directly this indicator relates to higher-dimensional athletic performance such as positioning and tactical decision-making in actual soccer games.

Furthermore, regarding effectiveness judgment in motor skill acquisition, research has scarcely progressed beyond laboratory stages to investigate how much acquisition speed was shortened or accuracy improved when teaching specific skills in actual field settings.

Absence of Effectiveness Verification Under Psychological Pressure

Cognitive improvements measured in controlled laboratory environments do not transfer to complex real-game situations. Laboratory studies are conducted under ideal conditions with minimal psychological stress. However, actual competitions involve high psychological pressure (anxiety, distraction, referee decisions, etc.), and research on whether combined tDCS interventions can maintain or enhance cognitive-motor performance under such conditions is virtually nonexistent. This represents a significant gap in evaluating the practical utility of interventions for enhancing sports performance.

In professional sports, although analysis at the laboratory stage is ultimately oriented toward improving athletes' competitive abilities, analyses should incorporate indicators reflecting the characteristics of relevant sports, and experiments should be conducted under various psychological pressures to contribute meaningfully to actual sport-specific performance enhancement.

4.4 Insufficient Research on Long-term Effects, Safety, and Ethical Issues

Systematic research is urgently needed regarding maintenance of long-term tDCS effects, safety with repeated use, and ethical implications of field application in sports.

Inadequacy of Long-term Effect and Safety Follow-up Studies

Most current literature is limited to immediate post-intervention or short-term follow-up observations (24 hours to 2 weeks). Studies examining effects after 8 weeks, such as Pan Shanchao (2024), are extremely rare. Evidence regarding whether effects persist months after intervention cessation, or conversely, whether dependence on training effects develops, is nearly absent.

Furthermore, studies systematically monitoring the long-term safety (neurophysiological and psychological aspects) of repeated tDCS application over months are very scarce.

Beyond short-term efficacy verification, longitudinal studies confirming the long-term effects of tDCS and safety with repeated use are essential.

Absence of Discussion on Sports Ethics Issues

"Neural enhancement" using tDCS may challenge the spirit of fairness in sports. This is an area that the World Anti-Doping Agency (WADA) is monitoring with interest. However, current research primarily focuses on efficacy verification and has failed to activate substantive discussion on the ethical justification of tDCS use in sports contexts, regulatory necessity, and implications for the concept of 'fair competition.' This is a task that must be preemptively addressed for the social acceptance of this technology and the establishment of future regulatory frameworks.

5. Future Research Prospects for Combined tDCS and Cognitive Task Application in Sports and Exercise

Synthesizing the literature analyzed in this study, the combined application of tDCS and Cognitive-related Tasks is emerging as a promising paradigm for enhancing sports performance, while simultaneously revealing multiple challenges that require resolution. Accordingly, future research directions and prospects need to evolve around the following five main axes.

5.1 Development of Optimized and Personalized Protocols

The most significant limitation of current research is the lack of standardization in stimulation parameters (site, intensity, duration) and application protocols (synchronization timing, period, frequency). Therefore, future research should proceed in the following directions:

Systematic Parameter Optimization

Dose-response studies are essential to identify the most effective stimulation sites (L-DLPFC, M1, SMA, etc.), intensities (1mA vs 2mA), and durations for specific sports types and training goals (attention enhancement, motor skill acquisition, fatigue recovery, etc.).

Elucidation of Synchronization Experimental Design

Systematic comparison of the effects of on-line (stimulation during task performance) versus off-line (stimulation before/after task performance) is needed to determine the most appropriate synchronization strategy for specific cognitive-motor tasks.

Personalized Approaches

Personalized protocols that account for individual difference variables such as individual brain structure/function, training history, and sport-specific characteristics must be developed. This will reduce inconsistency in effects observed despite identical protocols and maximize individual outcomes.

5.2 Securing Field Applicability and Ecological Validity Beyond the Laboratory

Since most studies have verified effects through simplified tasks in controlled laboratory environments, questions persist regarding whether results transfer to actual complex field settings.

- **Research Designs with High Ecological Validity**

  Research evaluating intervention effects in environments resembling real-world conditions (including competitive pressure, distracting elements, tactical decision-making) is necessary.

- **Utilization of Performance-Direct Indicators**

  Effectiveness verification should utilize indicators directly linked to actual athletic performance (e.g., pass accuracy, shooting decision accuracy, defensive positioning) beyond laboratory indicators (e.g., Stroop reaction time).

- **Long-term Field Research**

  Beyond short-term laboratory studies, research longitudinally intervening in actual training settings and comprehensively evaluating effects and feasibility is necessary.

5.3 Systematic Elucidation of Long-term Effects and Safety

Evidence regarding the sustained effects of combined tDCS interventions and safety of repeated application remains very limited.

Long-term Follow-up Studies

Longitudinal studies confirming whether effects persist for weeks to months after intervention cessation, or whether dependence on training effects develops, are essential.

Establishment of Safety Profiles

Systematic monitoring of the neurophysiological, cognitive, and psychological safety of long-term, repeated tDCS application over months and establishment of standard safety guidelines are necessary.

5.4 Deeper Elucidation of Neurophysiological Mechanisms

The neurophysiological mechanisms by which tDCS amplifies the effects of cognitive task performance have not yet been fully elucidated.

Various neurophysiological measurement indicators including EEG, fMRI, and EMG should be combined to multilaterally analyze the effects of combined intervention on brain excitability, functional connectivity, and neural network efficiency.

5.5 Proactive Discussion of Sports Ethics and Regulatory Frameworks

"Neural enhancement" via tDCS raises fundamental questions about fairness in sports and has become a subject of interest for the World Anti-Doping Agency (WADA).

Activation of Ethical Issues Discussion

Substantive interdisciplinary discussion should commence regarding the ethical justification of tDCS use in sports contexts, the concept of fair competition', and potential for misuse.

Foundation for Regulatory Framework Establishment

Research establishing the groundwork for ethical guidelines and regulatory frameworks for tDCS use in sports settings, in anticipation of future technological advancement and widespread adoption, is needed.

6. Conclusion

The combined intervention of tDCS and Cognitive-related Tasks is becoming an important component of the 'brain-centered training' paradigm for enhancing sports performance. This study has confirmed theoretical and empirical possibilities that this approach may exhibit superior amplification effects compared to single interventions in specific domains such as executive function, motor learning speed, and skill retention. However, numerous challenges requiring resolution remain, including non-standardization of stimulation parameters, insufficient consideration of individual differences, limitations of laboratory environments, and uncertainties regarding long-term effects and safety.

Therefore, future development in this field requires comprehensive and systematic research programs encompassing optimization, personalization, field transfer, mechanism elucidation, and ethical establishment—beyond simple efficacy verification. Through such efforts, the combined tDCS approach can finally realize its potential and establish itself as a scientific and responsible tool for maximizing athletic performance and promoting health in sports.

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