REVIEW ARTICLE

Transcranial Direct Current Stimulation and Executive Function in Athletes: A Comprehensive Review

Shahrouz Ghayebzadeh[1]

1 Department of Sport Management, Faculty of Education and Psychology, University of Mohaghegh Ardabili, Ardabil, Iran

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.

Abstract

Transcranial direct current stimulation (tDCS) has gained attention as a non-invasive brain stimulation technique with potential to enhance cognitive and executive functions in various populations, including athletes. In this review, we examined the effects of tDCS on cognitive and executive functions in athletes. Risky decision-making is a critical aspect of athletic performance, influencing choices related to strategy, tactics, and responses during gameplay. tDCS can improve decision-making abilities in athletes, particularly when targeting the dorsolateral prefrontal cortex (DLPFC). Enhanced DLPFC activity improves accuracy, speeds decision-making, and reduces impulsive choices. However, the effects of tDCS are also influenced by other factors such as electrode placement, stimulation parameters, and individual differences. Optimal protocol standardization and individualized approaches can maximize the benefits of tDCS in athletes. We also discussed the potential implications of tDCS for cognitive functions in sports and identified areas for future research.

Introduction

Risky decision-making relies on the ability to balance potential rewards against potential risks, whether it is deciding whether to invest in a new business opportunity or to take a risky shot on the goal in a soccer game[1]. In sports, decision-making is a critical aspect of performance[2][3]. Athletes are often required to make rapid and complex decisions in high-pressure situations, which can influence success on the pitch or the arena[4]. Risky decision-making plays an important role in sports performance as athletes must balance the potential benefits of taking risks with the potential costs of failure[5].

Various factors influence risky-decision-making, including individual differences, personality traits, emotions, and cognitive processes[6]. Recent research examined the potential of non-invasive brain stimulation techniques to enhance cognitive processes, including risky decision-making. One such technique gaining attention is transcranial direct current stimulation (tDCS).

TDCS is a non-invasive brain stimulation technique that involves the application of a low-intensity direct current to the scalp[7][8]. This technique is used to modulate cortical excitability, which potentially has therapeutic effects[9][10][11]. The electrodes for tDCS consist of an anode and a cathode, which are placed on the scalp over specific brain regions. The anode electrode is placed over the area of the brain that is to be stimulated, while the cathode electrode is placed over a non-stimulated area[12][13][14]. The direction of the current flow between the electrodes determines the polarity of the stimulation. When the anode is placed over the target area and the return electrode (cathode) is placed over a non-target area, this is referred to as anodal stimulation. Conversely, when the cathode is placed over the target area and the return electrode (anode) is placed over a non-target area, this is referred to as cathodal stimulation[15][16].

The stimulation duration in tDCS can vary by up to 20 minutes depending on the study design and the target brain region. The stimulation intensity typically ranges from 0.5-2 mA[12][17][13][14]. Depending on the chosen parameters, such as the duration of the treatment and the intensity of the current, cortical excitability in the target area can be either decreased or increased. Additionally, tDCS is relatively inexpensive and portable, which makes it a promising tool for research and potential clinical applications[18].

In general, tDCS has been used in a wide range of research areas, including cognitive neuroscience, motor control, and a variety of neurological and psychiatric disorders[9][19][10][11]. There is some evidence that tDCS can affect decision-making processes and risk-taking behavior in different populations[20][6], as well as cognitive processes such as attention and working memory[21][22][23].

Previous studies have also reported enhancements in attention[24], working memory[25], impulsivity[26], and learning[27]. Recently, Talar et al.[28] demonstrated in their systematic review with meta-analysis that beyond the cardiovascular and fitness benefits of aerobic exercise, pairing aerobic exercise with tDCS may have the potential to slow symptom progression of cognitive decline in mild cognitive impairment (MCI) and dementia[28].

The 2016 Olympic Games sparked media discussions about the traits and practices that differentiate ultrahigh performance athletes from others. The achievements of athletes like Phelps and Bolt highlighted the potential for prolonged dominance in competitive events[29]. This led to investigations into interventions such as neural brain stimulation[30], which has since resulted in the development of performance-enhancing products based on neuroscience[31][32]. A recent innovation in this area is “neuro-doping,” where athletes use electronic brain stimulation to enhance performance[33].

TDCS has been applied in various sports, including cycling[34], running[35], swimming[36], and eSports[37]. The technique aims to modulate motor cortex excitability, which can enhance movement precision, improve reaction times, reduce fatigue, and increase endurance[38][39][40]. Additionally, tDCS may boost attention and cognitive processing, which are crucial for rapid decision-making in sports[41][42][20]. Previous studies have demonstrated that tDCS can enhance attention[43], working memory[44], and learning abilities[45]. It may also improve risky decision-making by augmenting cognitive functions[40]. As our understanding of tDCS’s neuronal mechanisms advances, it could become a valuable tool for enhancing cognitive performance in sports[46].

However, the effects of tDCS on decision-making in sports are unclear. While some studies have suggested that tDCS can improve risky decision-making in sports[6], others have reported mixed[47] or even negative effects[48]. This article aims to provide a comprehensive review of the impact of tDCS on risky decision-making in athletes, including the effects of tDCS on decision-making, such as the specific brain regions targeted, the intensity and duration of the stimulation, and individual differences in cognitive abilities. We also discuss the potential use of tDCS as a tool for improving sports performance.

Methods

Research publications were retrieved from three main databases: (i) PubMed, (ii) Science Direct, and (iii) Google Scholar. The papers were published between 2010 – 2023. Review articles, meta-analyses, clinical trials and case reports were considered. Search terms such as tDCS, decision-making, risky-decision making, sport performance and cognitive and executive functions were used as keywords while searching the databases for relevant papers. Our search yielded 172 research articles. The corpus was further filtered for those papers applying tDCS in prefrontal cortex (PFC), ventromedial prefrontal cortex (vmPFC), dorsolateral prefrontal cortex (DLPFC) and investigating risky-decision making and/or cognitive and executive functions in athletes. After the exclusion of irrelevant literature (conference proceedings, papers without reference to athletes or tDCS), the search retrieved 40 hits, and after removing duplicates, we analysed 19 studies.

Types of decision-making in sport

Decision making is the process of identifying problems, opportunities, and selecting a course of action to resolve a problem or capitalize on an opportunity. It is a critical aspect of human life and an essential element in various endeavors such as business, education, healthcare, and even many daily activities[49].

The degree to which different cognitive processes contribute to a decision depends on the characteristics of the decision in question. One axis by which decisions can be differentiated is according to how much information is available on an expected outcome. Accordingly, there are two types of decision making: *Certainty decision making* and *Uncertainty decision making*[50].

1. Certainty decision making: This type of decision making occurs when the decision maker has information about all the alternatives, their outcomes, and the probabilities of those outcomes. In other words, the decision maker knows what will happen with each alternative and can predict the consequences with relative certainty. For example, a company may decide to invest in a project with a guaranteed return on investment[51][50].

2. Uncertainty decision making: This type of decision making occurs when the decision maker lacks all the information about the alternatives, their outcomes, and the probabilities of those outcomes. In other words, the decision maker does not know what will happen with each alternative and cannot predict the consequences with certainty. For example, a company may decide to invest in a new product that may or may not be successful in the market[51][52].

Uncertainty decision making has further subtypes:

- *Risky decision making:* This occurs when the decision maker has some information about the alternatives and their outcomes and can assign probabilities to each outcome[53]. A real world example of decision-making under risk is the decision to enter a raffle. In this scenario, an individual who purchases a ticket faces the possibility of either winning or losing, with the probability of winning being equal to 1 divided by the total number of tickets sold[54].
- *Ambiguity decision making:* This occurs when the decision maker lacks information about the alternatives and their outcomes and cannot assign probabilities to each outcome[55][56]. This type of decision making is much more common in everyday life, where the exact likelihood of events is often unknown. An example of ambiguity would be a person not knowing the chances of getting a new job they just interviewed for[55]. Or, a company may decide to invest in a new technology that is untested and has no clear market demand or competition.

Generally speaking, it can be said that in sports, the environment and all the environmental factors present in it affect the decision-making system and decision-making also affects the environment in turn. In this case, the probability of failure in deterministic decision-making is low, in risk-taking decision-making it is fifty-fifty, but in ambiguous decision-making the probability of failure is high (Figure 1)

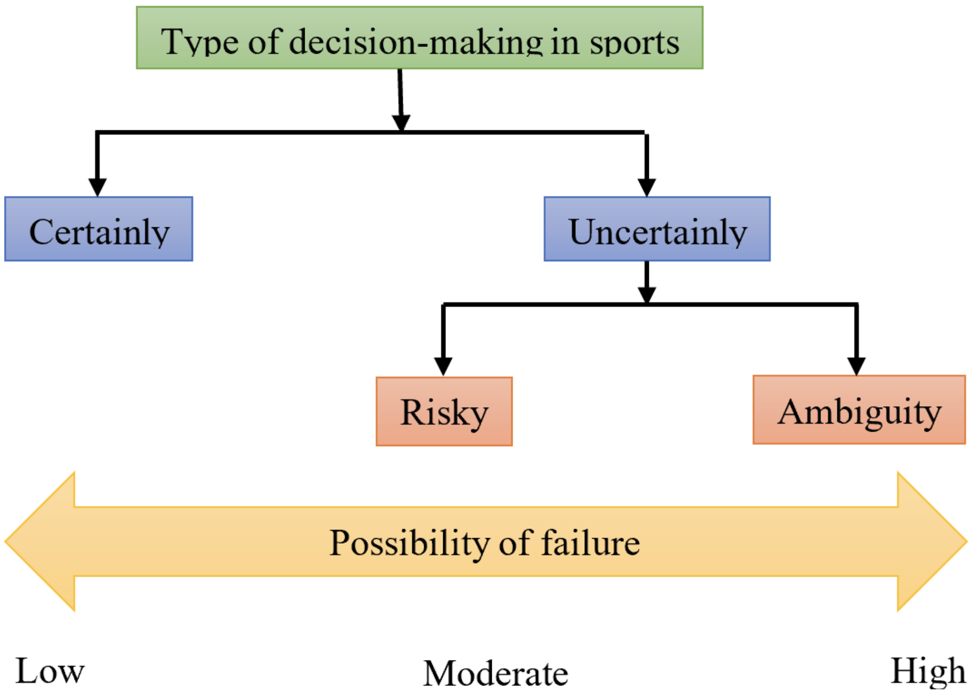

Figure 1. Decision making in sports

Decision-making in sports

Understanding the complexity of decision-making in sports is key to enhancing performance and success in the field[57]. Scholars have approached this topic from different perspectives, including classical decision-making, naturalistic, ecological, and intuitive approaches[58]. However, these perspectives have often remained isolated from one another, limiting their practical impact on sports performance[59].

Sports provides a unique opportunity to appreciate the intricacies of decision-making[60]. Sports decision-making involves a myriad of factors, encompassing the decision-makers themselves (referees, coaches, athletes, etc.), the tasks at hand (ball possession, physical contact, etc.), and the contexts in which decisions are made (during gameplay, timeouts, etc)[61][62][63][64].

The process of decision-making in sports is heavily influenced by environmental and temporal conditions, as well as the rules and regulations governing the game[65][66]. The specific conditions can vary significantly depending on the sport. For instance, in dynamic sports (e.g. football, futsal, volleyball, basketball, and handball), the environment is constantly changing and unpredictable. The movements of teammates and opponents directly impacts an individual's performance. In such dynamic situations, decisions must be made instantaneously, and athletes need to understand what needs to be done, how, and when to react. These decisive moments significantly contribute to an athlete's success in executing their actions[61][67][64]. On the other hand, closed skill sports (e.g. rifle shooting, archery) have more stable and predictable conditions[68][69]. Athletes in these sports can anticipate their moves in advance, plan their responses beforehand, and execute them without the need for real-time adjustments[68][70].

Importantly, each combination of decision-making factors creates a distinct and intricate interaction of various elements that influence the decision-making process in sports[59]. Based on this, in ball sports such as football, basketball, and handball, which are dynamic and highly interactive, various internal factors influence decision-making due to time constraints during the game[71]. As a result, decision-making patterns may vary widely across different sports and scenarios. These internal factors include stress[72], emotions[73], impulsivity[74], reaction times[75], personality traits[76], fatigue[77], and gender[78][79] In the following, we will briefly examine factors that greatly impact executive performance and decision-making of athletes.

If we consider a sporting event as an organization, then we can assume that sporting events will also face uncertainty as in other organizations where every decision-making process culminates in a final choice that results in either success or failure[80][81]. A particular type of this process, known as risk-taking decision-making, occurs in situations where an individual is faced with options that entail potential gains and losses, both immediate and in the future[82]. This type of decision-making is one of the most important cognitive processes in sports[83]. For example, the judgments of referees in sporting events play a crucial role in the outcome of a sports event. This falls under the category of risk-taking decision-making[20], and the nature of this type of decision-making varies depending on the nature of the sport[84]. In individual sports, such as golf or tennis, athletes must make strategic decisions regarding shot selection and risk-taking in order to outperform their opponents. Similarly, in team sports such as soccer or basketball, athletes must make decisions regarding ball possession, passing, and shooting that involve taking calculated risks.

Individuals participating in various sports exhibit variations in their willingness and ability to make risky decisions, and it is commonly believed that such behavior can be attributed to their individual differences[85][86]. A study by Raab and Johnson's[87] sheds light on the relationship between action orientation and risk-taking behavior in sports, which are referred to how individuals cope with stressful or challenging situations in sports activities. The study revealed that athletes with a higher action orientation *(willing / likely to act)* are more likely to take risks in sports, while those with a lower action orientation are less likely to do so. Action orientation is the tendency to focus on taking action rather than on one's own emotions or thoughts when faced with a difficult or demanding task. Thus, action-oriented individuals are more likely to overcome obstacles, persist in their goals, and perform well under pressure. The findings of the study highlight the importance of understanding individual differences in action orientation to comprehend risk-taking behavior in sports[87]. An example of individual differences that affects decision-making is the individual's mental state at different times, which is largely shaped by their emotions; in other words, the individual experiences particular states within themselves for every external action and expresses it; in fact, this is the personal experience at every moment in time. Some tasks such as taking a test, participating in a sports competition or job interview creates intense emotional reactions in humans to the extent that it can affect their performance[88][89]. A study by Zhang & Shou[90] examined the role of immediate emotions and subjective stakes in risky decision-making under uncertainty. The authors argue that emotional reactions can have a significant impact on people's decision-making processes, particularly in situations with a high degree of uncertainty. They also suggested that individuals are more likely to take risks when they feel that the stakes are high and that they have something to gain or lose, and conclude that understanding the role of emotions and subjective stakes in decision-making can help individuals and organizations make better choices and improve their overall decision-making processes[90]. Various studies propose that individual differences in emotions refer to the fact that people vary in the way they experience and express emotions: some people may be more prone to experiencing intense emotions, while others may be more likely to suppress their emotions. These individual differences can influence decision-making processes, as emotions can impact how risks and rewards are perceived and evaluated.

Personality traits in individuals affects their risky decision-making behavious. Astudy by Lauriola & Levin,[91] examined the relationship between personality traits and risky decision-making using a controlled experimental task under the assumption that personality traits could influence the way individuals assess and respond to risky situations. Their findings suggests that some personality traits, such as extraversion and openness to experience, are associated with increased risk-taking behavior[91].

Gender is another factor that can also influence decision-making, as shown in a study showing that males and females approached decision-making differently based om socialization, cultural norms, and biological differences[92]. Another study by Frick[93] that investigated gender differences in risk-taking and sensation-seeking behavior in the context of extreme sports (cliff diving and free diving) suggested that men are more likely than women to engage in extreme sports and to report higher levels of both risk-taking and sensation-seeking behaviors. However, the author also noted that women who participated in extreme sports tended to report higher levels of sensation-seeking behaviors than women who did not participate. These findings may be related to social and cultural norms, as well as individual differences in personality and motivation, highlighting the importance of gender differences in risk-taking and sensation-seeking behaviors in the context of extreme sports and beyond[93].

Another factor often that is overlooked is the context in which decisions are made[94][95], particularly for elite athletes who face various mental and physical stresses (e.g.physical exhaustion, injury, negative feedback, pressure to win awards etc) which can lead to reduced them performance[96][97]. Soccer players perform worse in penalty shots that could cost the team winning the game (high-pressure, 62% success rate) compared to penalty shots that would secure the team's win (low-pressure, 92% success rate)[98]. Additionally, golfers tend to perform worse in the final round of a tournament when the pressure is at its highest, compared to the penultimate round[99].

Many situations in sports competitions require quick decision-making based on reflection and contemplation of all possible responses[80][81]. In such sports positions, having a functional impulsivity and optimal reaction time improves sports performance[100]. Impulsivity refers to a tendency to act quickly without considering the potential consequences of one's actions, and involves making hasty decisions or engaging in impulsive behaviors without fully thinking through the potential outcomes, and is often associated with a lack of self-control and risk-taking behavior[101][102]. This definition indicates that impulsivity is an inefficient state that leads to undesirable consequences[103]. However, due to unique circumstances, impulsive behavior does not always result in negative outcomes. In fact, in some cases, impulsivity can lead to desirable responses[104][103]. This means that impulsivity is not a simple or fixed trait, but rather a complex and context-dependent phenomenon. The term "functional impulsivity" was coined to describe this aspect of impulsivity and its relationship to the decision-making process[104]. It should be noted that the term "functional impulsivity" is the ability to act quickly and effectively in situations that require fast and adaptive responses, such as driving or sports. It can prevent negative outcomes that can result from delaying or overthinking, such as accidents, mistakes, or dissatisfaction from the stakeholders of sports events[104][103][105]. For example, we often demonstrate quick reactions while driving when other drivers are driving recklessly. These certainly prevent disasters, but we do them without prior thought. Similarly, in complex situations during sports' events, such as football or basketball, delayed reactions and decisions can cause undesirable responses from the stakeholders; This is exactly when functional impulsivity can be effective[106][20]. In general, it can be said that Impulsivity can sometimes be good and lead to positive results. This shows that impulsivity is a situation-dependent one.

Another useful indicator for assessing the speed and efficiency of risky decision-making, particularly in sports, is reaction time (RT)[20],.which is defined as the time interval between the presentation of a stimulus and the onset of the response[100]. RT can vary with the complexity of the task, with some tasks requiring simple responses to basic stimuli, while others involve more complex decision-making and cognitive processing[107]. In sports, RT has a key role role in determining performance, especially in sports that necessitate quick reflexes such as boxing or tennis. In team sports competitions, sports referees' decision-making must align with observed actions in the shortest possible time to avoid possible objections from athletes, coaches, and spectators[108]. A significant negative correlation between impulsivity and RT has been reported, where more impulsive individuals tend to have shorter RTs[109].

These findings suggest that understanding these internal factors and how they interact with one another is crucial for optimizing decision-making and performance in sports. Coaches and sports psychologists can partner with athletes to develop strategies for managing stress, regulating emotions, balancing impulsivity, improving reaction time, and leveraging personality trait.

Brain regions involved in risky decision making modulated by tDCS

Several brain regions have been implicated in risky decision making, and tDCS can be used to selectively target and modulate the activity of these regions. One key area is PFC, which is involved in executive functions such as working memory, attention, and decision making. Specifically, DLPFC and vmPFC are particularly important for risky decision making[110][111].

However, some studies reported that using tDCS to modulate activity in the DLPFC can lead to more risky decision making, suggesting that the DLPFC plays a role in regulating impulsive behavior[110][112]. In addition, applying tDCS to the vmPFC can also increase risk-taking behavior, indicating that the vmPFC may be involved in processing the potential rewards of risky choices and influencing decision making accordingly[110][111].

Other brain regions also implicated in risky decision making include the insula (which is involved in processing emotions and interoceptive signals) and the striatum (which is involved in reward processing and habit formation)[113][114]. tDCS can also be used to modulate activity in these regions, although the specific effects may depend on the individual and the task being performed.

Overall, tDCS can be a useful tool for investigating the neural mechanisms underlying risky decision making, and for exploring potential interventions to modify this behavior. However, it is important to note that tDCS is a relatively new technique and more extensive research is needed to better understand its effects and potential applications.

Synergy between tDCS and cognitive behavioral functions in sports

Cognitive and neural research has recently gained greater interest[115], and the past two decades led to the idea of studying the combination of cognitive neuroscience and sports to focus on interdisciplinary studies in management, neurosciences, and their relationship with cognitive functions in sports[116][117][32], later stimulating investigations on the use of non-invasive electrical stimulation to enhance the executive, cognitive, and behavioral performance of athletes[118][119][41]. The current data on decision-making in sports has been gained largely through traditional methods such as questionnaires, interviews, self-reports, or reports from others. However, findings cognitive neuroscience methods are more accurate in terms of evaluation compared to studies conducted using interviews and questionnaires[120][121][122].

Research on the effectiveness and efficiency of non-invasive brain stimulation methods on athletes has recently increased. The impact of non-invasive brain stimulation on decision-making in athletes to determine whether manipulating activity in these brain regions can influence decision-making or improve decision-making skills have recently been studied[40][51][41]. The convergence of neuroscience and organizational science presents a uniquen opportunity to gain new insights into managerial phenomena and cognitive functions, and importantly, can provide greater insight into behaviours such as risky decision-making, impulsivity, reaction time, personality traits, gender, and emotion regulation.

Recent findings in cognitive neuroscience indicates that risky decision-making processes are associated with specific regions of the brain (Figure 3). Studies by Ghayebzadeh et al.[6][20] reported that tDCS applied to the right dorsolateral prefrontal cortex (r-DLPFC) improved risky decision-making while increasing impulsivity and reducing reaction times in male and female sports referees, though it did not affect leadership styles. Risky decision-making and impulsivity rose and reaction time decreased with r-DLPFC stimulation in both genders[20][6]. Additionally, repeated tDCS over the left dorsolateral prefrontal cortex (l-DLPFC) before training enhanced cognitive performance and decision-making speed in soccer players[40]. In addition, tDCS modulates risk-taking and promotes aggressive pacing in athletes[123], while tDCS of the motor cortex improved reaction times and improved impulsivity in both athletes and non-athletes similarly[124], suggesting that tDCS may be a promising new tool for boosting skill acquisition and decision-making in sports training[125]. Cyclists who received tDCS had significantly longer times to exhaustion compared to the control group who did not receive tDCS, suggesting that tDCS enhances cycling performance by improving motor cortex excitability and reducing perceived exertion during exercise[126]. In addition, tDCS improved reaction time, attention, and decision-making in power athletes without affecting working memory or motor performance[118]. Athletic pacing based on risk-taking tendencies is also incraesed by tDCS, as shown by improved cycling time trial performances especially for high risk-takers[123]. There is also evidence that tDCS has benefits in eSports, where it can potentially enhance cognitive and motor skills like attention, decision-making, and reaction time critical[127]. Other studies indicate that single sessions of active tDCS reduced pre-competition anxiety and negative mood in elite athletes[128], and improved emotion regulation, particularly suppressing depression and anxiety, in healthy volunteers[129].

Recent findings report that tDCS decreases risk-taking most in impulsive and sensation-seeking personalities by modulating prefrontal activity underlying cognitive control[130]. Furthermore, Borducchi et al.[29] found active tDCS enhanced attention, working memory, and decision-making in athletes compared with sham stimulation[29]. Recent studies have investigated the effects of tDCS applied to the left dorsolateral prefrontal cortex (DLPFC) on various cognitive and emotional processes. One study found that anodal tDCS over the left DLPFC enhanced emotion regulation by promoting adaptive strategies such as reappraisal and reducing maladaptive strategies like emotional suppression[129]. Another study showed that anodal tDCS of the left DLPFC reduced the adverse effects of mental fatigue on 50-meter swimming performance in professional swimmers, while cathodal stimulation had no significant effect[36]. Application of tDCS to the left DLPFC improved working memory and shooting performance in professional female basketball players during prolonged cognitive tasks[119]. Finally, another study demonstrated that anodal tDCS to the left DLPFC reduced negative emotional reactivity to unpleasant stimuli, with greater effects seen in introverts compared to extraverts[131].

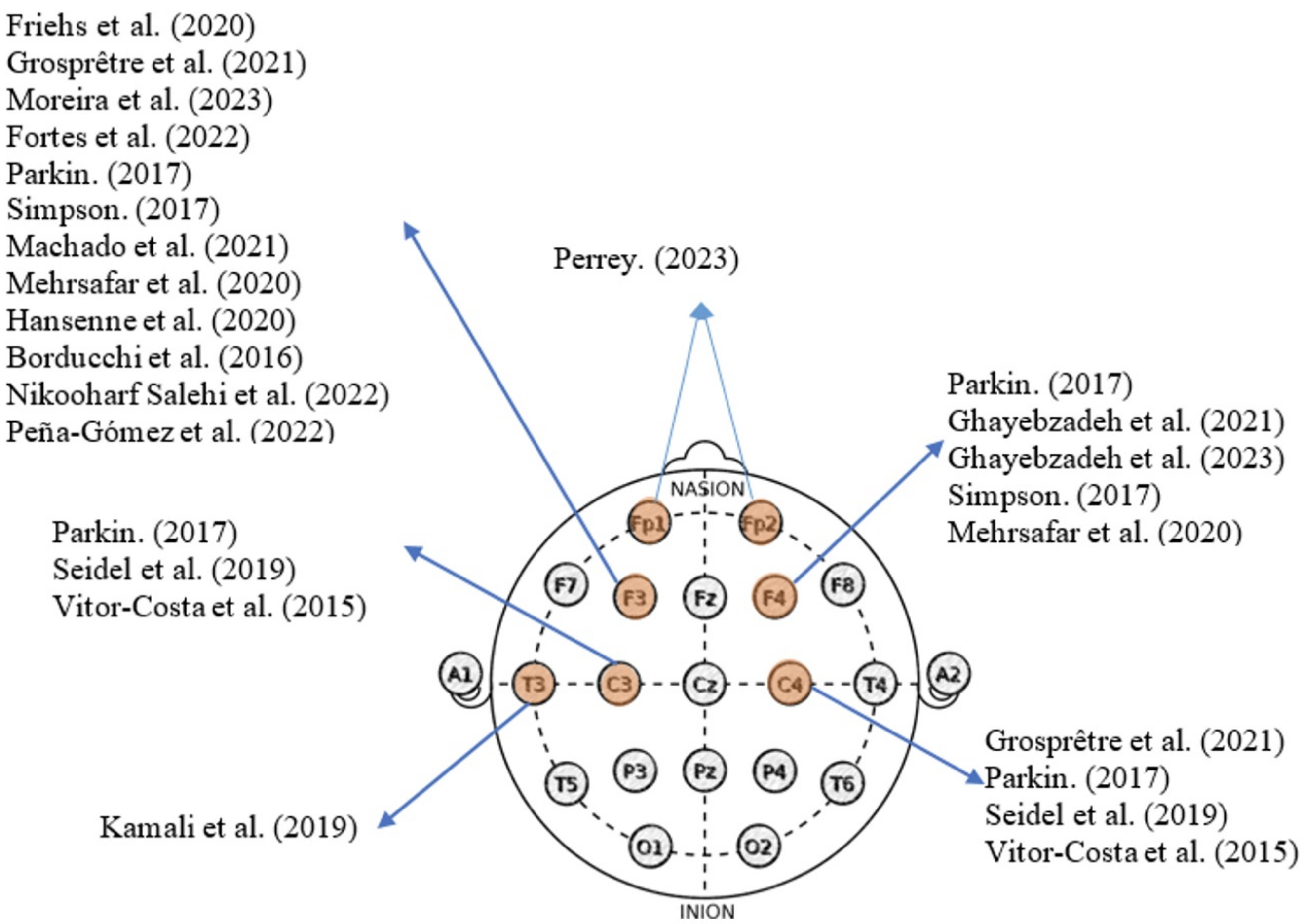

Figure 2. tDCS and executive and cognitive functions: a summary of the available literature. The list of studies targeting different brain regions of interest. Note: electrodes locations refer to the 10–20 EEG system

The general framework of this study is designed as follows:

The type of tDCS (unilateral or bilateral), the type of stimulation (Anodal, Cathodal, or sham), the duration of stimulation (up to 20 minutes), and the intensity of stimulation (0.5 to 2 mA) depending on the research objectives.

The choice of brain regions (DLPFC, PFC, vmPFC,...) for stimulation also depends on the cognitive functions in the brain lobes. For example, the frontal lobe controls body movement, personality, problem-solving, concentration, planning, emotional reactions, sense of smell, word meaning, and general speech. The parietal lobe controls sense of touch and pressure, taste, and bodily awareness. The temporal lobe governs hearing, face recognition, emotions, and long-term memory. The occipital lobe controls vision. The cerebellum regulates fine motor control, balance, and coordination. The limbic lobe controls emotions. Based on these different functions, it is necessary to identify which region of the brain is involved in decision-making. Then, the tasks used (IGT, BART, GO NO GO, DOSPERT,...) for the cognitive variables (RDM, FT, IMP, WM, S, E, ID,...) are selected based on previous studies. Finally, after analyzing these tasks, the effect of tDCS on the cognitive variables is determined by comparing the pre-test and post-test results (positive, negative, or ineffective effect) (Figure 3).

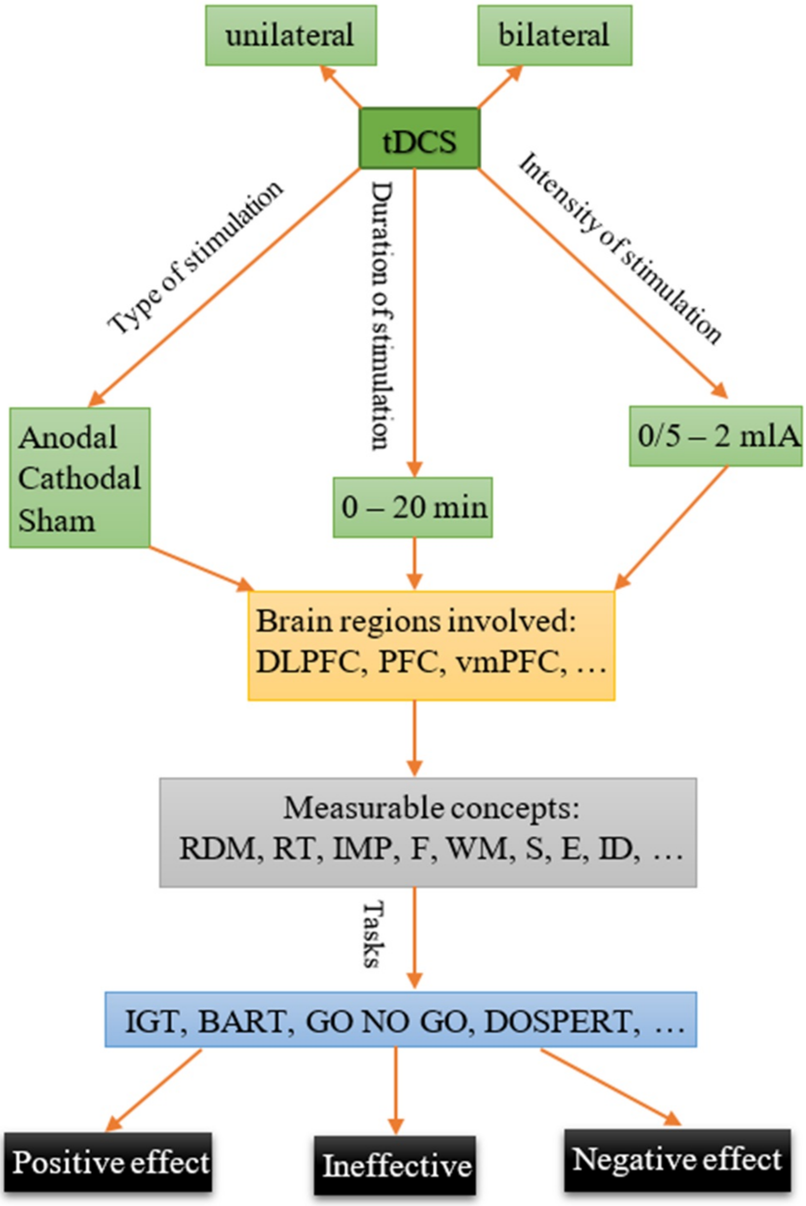

Figure 3. Study flow chart. tDCS = transcranial direct current stimulation; DLPFC = dorsolateral prefrontal cortex, PFC = prefrontal cortex, ventromedial prefrontal cortex = vmPFC, RDM = Risky decision-making, RT= reaction-time, IMP = Impulsivity, F = Fatigue, WM = working memory, S = Stress, Emotions, ID = Individual differences, IGT = Iowa gambling task, BART = Balloon analogue risk task, DOSPERT = Domain-Specific Risk-Taking

Limitations

Findings of cognitive neuroscience research in athletes who have used tDCS as a non-invasive method to enhance decision-making processes seems somewhat challenging, in large part because none of these studies targeted the same region of the cortical area. Consequently, differences in the number of participating samples, the tasks used for decision-making processes (such as the Iowa Gambling Task, Bart, Go/No-Go, etc.), and the stimulation protocol potentially introduce inconsistencies in the research outcomes.

Additionally, there are limitations to generalizing the results of athletes from different sports. Decision-making processes in sports can vary based on skill categorization (open and closed skills). Open skills are those that are performed in a dynamic and unpredictable environment. The athlete must adapt their movements and decision-making based on the changing conditions of the game or the actions of opponents. Examples of open skills include playing defense in soccer, reacting to an opponent's moves in boxing, or making split-second decisions in team sports like basketball or hockey. On the other hand, closed skills are those that are performed in a stable and predictable environment. The athlete has control over the timing and execution of the skill because the environmental conditions are relatively constant. Examples of closed skills include shooting a free throw in basketball, serving a tennis ball, or performing a gymnastics routine. Apart from these factors, the stimulated brain region, duration and intensity of stimulation, type of stimulation, and number of stimulation sessions differ across various research studies. Also, there are other regions in the brain that play a crucial role in decision-making processes, but their exact mechanisms are still unknown.

However, further research is required to validate these findings and establish the optimal parameters for implementing tDCS in athletes. It remains uncertain whether similar results would be observed in other athletes or individuals who are not athletes. Additionally, it is unclear whether the effects of tDCS would be long-lasting.

Conclusion

This review indicates that tDCS has promise as an intervention for enhancing cognitive and motor performance in athletes. One particular focus of interest is the dorsolateral prefrontal cortex (DLPFC), which plays a critical role in executive functions and attention. The potential benefits of stimulating this region could aid athletes during training or competitions by improving their focus and decision-making abilities. While the potential advantages of tDCS in sports are promising, it is crucial to exercise caution when approaching this technology. The field of tDCS is still in its infancy, necessitating further research to fully comprehend its mechanisms and long-term effects. Moreover, individual responses to tDCS may vary due to factors such as age, gender, and baseline cognitive or motor abilities, resulting in different levels of cognitive enhancement. On the other hands, it is essential to address ethical considerations and establish regulations. Like any performance-enhancing method, there is a risk of creating an unfair advantage, thus guidelines should be established by regulators to ensure responsible usage of tDCS in sports.

Currently, there is encouraging data in the field of cognitive neuroscience. The therapeutic application of tDC so far has been investigated in a number of variables of cognitive neuroscience, such as decision-making, impulsivity, reaction time, working memory, attention, concentration, emotions, stress, fatigue, and more. These studies examined the combined use of tDCS with other tools in physiotherapy to treat individuals with movement disorders resulting from some diseases and to improve the executive and cognitive functions of both healthy individuals and athletes in various sports disciplines. Therefore, considering ethical and legal aspects, the use of tDCS as a diagnostic tool can be highly beneficial and impactful.

While the future of tDCS in enhancing cognitive performance in sports and other areas appears promising, additional research and thoughtful consideration of ethical implications are necessary. Through continued scientific exploration and responsible implementation, tDCS has the potential to optimize athletes' performance.

Statements and Declarations

Ethics approval and consent to participate

Not applicable.

Availability of data and material

All data supporting the findings of this study are available in this published article.

Conflicts of interest

The authors declare that they have no competing interest.

Funding

This study received no external funding.

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