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The influence of specific cognitive-motor training in virtual reality on the executive functions of competitive athletes and identification of the related neural bases

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Abstract

This doctoral thesis investigates the effects of cognitive-motor dual-task (CMDT) training implemented in virtual reality (VR) on anticipatory and decision-making cognitive functions and related electrophysiological correlates in professional and semi-professional athletes in open-skill sports. This is because these sports require the simultaneous management of perceptual, cognitive, and motor processes in dynamic and unpredictable environments. Despite this, traditional training methodologies continue to favour technical and physical aspects, neglecting the systematic training of cognitive functions. The main objective of this thesis was therefore to analyse the influence of specific CMDT-VR training on the physical and cognitive performance of athletes. Through five complementary studies, this dissertation progressively analysed the cognitive-motor plasticity induced by different CMDT-VR protocols, using behavioural and neurophysiological measures. Specifically, the first study, conducted on young adults, aimed to validate a CMDT training paradigm in VR. This protocol, centred on visuomotor readiness and perceptual discrimination exercises, produced effects at both the behavioural and electrophysiological (EEG) levels. Participants exhibited faster response times and higher response accuracy, accompanied by increased amplitudes of the anticipatory pN and BP. The second study, conducted on semi-elite young soccer players, confirmed and expanded upon these results. Integrating a sport-specific CMDT protocol within the regular training routine led to significant improvements in response speed and response accuracy, paralleled by enhanced activity in the prefrontal and premotor anticipatory event-related potentials (ERP) components derived from EEG. This evidence suggests a potentiation of top-down cognitive control and motor preparation, both of which are fundamental to anticipatory and action-planning mechanisms. The third study broadened the analysis to include post-stimulus ERP components, revealing increased amplitudes in early and late components. Then, considering the limited literature on the neural correlates of dance expertise, I conducted a fourth study aimed at identifying the cognitive functions that characterize professional dancers compared to athletes from other disciplines. Results revealed a pronounced enhancement of the anticipatory brain activity accompanied by a reduction in reactive activity during a cognitive task. On these findings, a fifth and final study was conducted to examine the effects of a specific CMDT-

VR training protocol on both the cognitive performance and motor skills of professional dancers. The results showed significant improvements in response accuracy and postural stability. These behavioural enhancements were accompanied by increased anticipatory prefrontal activity. Conversely, motor preparation and response times were not significantly modified by the training. From an applied perspective, the findings of this doctoral research highlight the potential of virtual reality as a strategic complement to conventional sports training, effectively integrating the cognitive dimension into technical and tactical practice. The implementation of CMDT protocols in VR enables athletes to train executive and anticipatory functions within an immersive, safe, and fully controllable environment, engaging in decision-making, attentional, and anticipatory challenges closely resembling real-game demands, yet with the advantage of high reproducibility, intensive repetition, and immediate feedback.

Introduction

Open-skill sports, such as football, dance or martial arts, are characterized by high variability and unpredictability of the environment, which forces athletes to adapt their motor actions in real time to changing external conditions. In such disciplines, performance depends not only on physical efficiency or technical and tactical mastery, but above all on the ability to quickly process sensory information, anticipate events and select the most effective response (Vestberg et al., 2012; Memmert & Roca, 2019). The unpredictability of the context and the need for rapid and accurate responses make these sports a privileged model for studying the neurocognitive mechanisms underlying human performance (Furley & Wood, 2016). Numerous neuroscientific studies have shown that, in open-skill sports, cognitive function is a crucial determinant of performance success. Processes such as selective attention, cognitive flexibility, working memory, and rapid decision-making enable athletes to filter relevant stimuli, construct predictive representations of the environment, and plan actions with high efficiency (Vestberg et al., 2017; Roca et al., 2018). These processes are supported by distributed brain circuits involving the prefrontal, parietal and premotor areas, which orchestrate the integration of perception, cognition and movement (Di Russo et al., 2019; Wang et al., 2020). In this sense, high-level sports performance emerges as the result of optimized interaction between sensory, cognitive and motor systems, according to the perceptual-motor integration paradigm (Neumann et al., 2018). Although sports literature has developed a wide range of motor training methodologies capable of enhancing strength, endurance and coordination (Morgans et al., 2014; Thapa et al., 2021), systematic training of cognitive functions remains a methodological gap (Scharfen & Memmert, 2019; Staiano et al., 2022). In fact, traditional cognitive protocols often fail to reproduce the situational complexity typical of the sporting context, while the real environment limits the possibility of exercising rigorous experimental control over stimuli and cognitive loads (Dallaway et al., 2021). As a result, athletes are rarely exposed, in a structured and repeatable way, to stimuli that can train the anticipatory, decision-making and attentional components that support performance under conditions of pressure and uncertainty.

Aim of the dissertation

This doctoral thesis aims to investigate the effects of specific dual-task cognitive-motor training (CMDT) paradigms applied through virtual reality (VR), with the goal of enhancing anticipatory and decision-making cognitive functions in open-skill sports contexts. CMDT in VR, adapted from protocols previously validated in basketball (Lucia et al., 2022; 2023a; 2023b; 2024a), combines motor and cognitive exercises in an immersive and controlled environment, allowing for the simultaneous stimulation of attention, inhibition, working memory and motor planning processes. Through electrophysiological measures (EEG and ERP), the thesis aims to analyze changes in the neural correlates of anticipation and decision-making, verifying the functional plasticity induced by VR training.

Chapter 1: The study of cognitive function

1.1 Main models and empirical findings

Executive functions (EFs) are defined by Stuss (1992) as “*a set of abilities that allow individuals to formulate goals, retain them in memory, control actions, and anticipate obstacles to goal attainment.*” These abilities are what allow us to solve problems, organize and direct our actions, and comprehend abstract or difficult ideas (Cristofori et al., 2020). Over the years, several authors have attempted to define this complex and multifactorial construct. For example, Diamond (2020) recent papers, best defined EFs as a complex collection of cognitive abilities that include working memory, inhibitory control, cognitive flexibility, planning, reasoning, and problem solving. The executive system manages and controls other cognitive abilities (e.g., attention and memory) and allows individuals to alter their overlearned behavioral patterns when they become unsatisfactory (Van der Linden et al., 2000). It enables adaptation to novel and complex everyday life situations too (Collette et al., 2006). Instead, long-standing studies such as Blair and Razza (2007) used the so-called *effortful control* to describe what EFs were. Specifically, *effortful control* refers to the ability to regulate behavior by inhibiting a dominant behavior, should the context so require (Chae, 2022). However, according to other authors (Smith & Jonides, 1999; Miyake, Friedman, Emerson, Witzki, and Howerter 2000), EFs go beyond this, addressing concepts like working memory, cognitive flexibility, problem solving, and the execution of all those goal-directed activities in addition to the inhibition of irrelevant information. Chan, Shum, Touloupoulou and Chen (2008), in defining EFs, made a substantial difference between cold and warm components. In this sense, all the aforementioned functions (working memory, cognitive flexibility, etc.) would constitute the cold component because they would correspond to mechanistic and logic-based processes that would have nothing to do with emotional activation. On the other hand, they would also be implicated in modulating complex emotional responses, in the identification and evaluation of punishments and rewards, and in decision-making processes. These functions, given the prominent role of the emotional component, would constitute hot components. Among the various theoretical framings, is it possible to include models that distinguished them as a unitary construct (Shallice, 1982; Norman and Shallice, 1986; Baddeley, 1990), or as a function of their contribution to overcoming complex tasks (Lezak, 1983; Burgess, Veitch, De Lacy Costello and Shallice, 2000) or as a series of different but highly integrated functions (Smith and Jonides, 1999; Miyake et al.,

2000, Ladavas and Berti, 2014). With regard to unitary models, Norman and Shallice's (1986) attention-to-action model involves a Supervisory Attentional System (SAS) that handles two sub-components: action schemata and competitive cataloguing. Action schemata are specialized in routine activities triggered automatically by the appearance of specific stimuli. Different action schemata can be triggered simultaneously by different stimulus-triggers. In these cases, the action patterns conflict with each other with the result that one will tend to inhibit the other. It is in this context that competitive cataloguing intervenes: a semi-automatic mechanism for selecting patterns of action. Both patterns of action and competitive cataloguing are controlled by the SAS involved in the control of top-down processes and which allows behavior to be guided in a reflexive and voluntary manner. A concept superimposed on the Supervisory Attentional System was expressed by Baddeley and Hitch (1974) and later Baddeley (1990) theorized the existence of a centralized system. Baddeley refers to the concept of the central executive, i.e. an attentional system that coordinates three subsystems: the phonological loop responsible for linguistic processing, the visuospatial notebook involved in the processing of non-verbal visual-spatial material, and the episodic buffer responsible for the integration and exchange of information between the other subsystems. Thus, the central executive would have multiple functions. It excludes irrelevant stimuli, provides the ability to pay attention to multiple stimuli and allows cognitive flexibility. Other authors analyze EFs from the perspective of a procedural series of actions to be performed in order to complete a task. Lezak (1983) proposes the existence of four types of EFs that would intervene sequentially in the solution of complex tasks. First, it is necessary to formulate goals, a skill that requires the individual to conceptualize the present and to think about it using prospective memory. Subsequently, planning intervenes, whereby the subject must evaluate the steps necessary to achieve the goal. After planning, there is the implementation of the behaviors necessary to achieve the goal. Finally, effective performance is only possible through self-monitoring and self-correction. According to Burgess and colleagues too (2000), complex tasks would be decomposable in a series of sequences in which EFs would intervene. The latter would be involved in learning the rules of the task, in planning and implementation and, finally, in checking the degree of consistency between what was planned and what was executed in order to make appropriate corrections if necessary. Finally, a number of authors (Pennington and Ozonoff, 1996; Smith and Jonides, 1999; Miyake and colleagues, 2000; Alvarez and Emory, 2006; Blair and Razza, 2007; Greene, Braet, Johnson and Bellgrove, 2008; Ladavas and Berti, 2014)

speak of Executive Functions as different but closely related processes. Thus, what is certain to date is the complexity in accurately defining the construct of executive function, given the multiplicity of theoretical models proposed. Some authors have emphasized its unitary nature, attributing its control to a superordinate central system (Norman & Shallice, 1986; Baddeley, 1990), while others have described its procedural nature, functional for solving complex tasks (Lezak, 1983; Burgess et al., 2000). More recent models adopt a multicomponent perspective, recognizing EFs as a set of distinct but interconnected processes, regulated by both cold cognitive and warm affective mechanisms (Miyake et al., 2000; Chan et al., 2008). Considering this heterogeneity, it is essential to investigate the neuroanatomical localization of executive functions and to understand which cortical and subcortical structures support their processing. EFs have been linked to the frontal lobes for many years. This connection was first made in the well-known instance of Phineas Gage, who in 1848 was employed at a railroad construction job when a big iron rod went through his left frontal lobe. The earliest recorded proof of the complexity of EFs and their brain foundation was provided by Phineas Gage, who survived this event but had significantly changed behavior and personality (Ratiu et al., 2004). Numerous evidence supports the central role of the prefrontal cortex (PFC) in the implementation of executive functions. It is one of the most developed cortical areas in humans, occupying more than one third of the total cortical surface area (Smith & Jonides, 1999), and is at the same time one of the phylogenetically most recent regions, characterized by a slow maturation process during development (Fancello et al., 2006; Lådavas & Berti, 2014). Its importance also lies in its high connectivity: the PFC is interconnected with cortical and subcortical motor areas, with sensory systems, and with limbic and midbrain structures involved in emotional regulation, memory and reward circuits (Lådavas & Berti, 2014). This complex network of connections allows the prefrontal cortex to exert flexible and adaptive executive control. Lesions in this area frequently result in behavioral disorganization, impulsivity and an inability to modify cognitive and motor strategies in response to environmental changes (Lezak, 1983). In patients with frontal damage, perseveration errors are frequently observed, i.e. rigid and repetitive responses that are no longer functional to the task (Nelson, 1976), as well as impairments in verbal fluency, working memory and inhibitory processes (Alvarez & Emory, 2006). Duncan and colleagues (2000) described these subjects as incapable of pursuing set goals, with a tendency to neglect them despite retaining a mental representation of them: a phenomenon termed goal-neglect (Duncan, 2000). Moreover, according to Elliott (2003),

prefrontal damage is associated with impairment of judgement, decision-making incapacity, disinhibition and deterioration of intellectual abilities. Historically, Luria (1966; 1973) had already described the PFC as a superstructure deputed to the control of mental and behavioral activity: damage to this area impairs the planning of complex sequences, favoring the enactment of stereotyped behavior, lacking logical coherence or relevance to the context (Chan et al., 2008). In a more articulated model, Stuss and Benson (1986) proposed that executive control is sustained by the interaction of three systems: the anterior ascending reticular activating reticular system (ARAS), responsible for the tonic level of activation and vigilance; the diffuse thalamic projection system, implicated in phasic attention to external stimuli; and the fronto-thalamic system, which regulates higher-level processes such as planning, response selection, and performance monitoring. Damage to these systems is associated with impaired consciousness, inattention to environmental stimuli, and deficits in strategic control mechanisms, respectively. Also, according to Stuss and Benson, specific cognitive functions would be attributable to sub-regions of the prefrontal cortex: sustained attention to the right PFC, concentration to the cingulate cortex, divided attention to the orbitofrontal area and the cingulate, while the dorsolateral PFC would oversee the inhibition of irrelevant responses, preparation for action, and goal setting. Switching, i.e., the ability to switch from one strategy or response to another, would involve the dorsolateral and medial regions of the PFC. In light of this evidence, they propose a functional distinction between lateral prefrontal cortex (LPFC) and orbito-medial cortex (OFC), each implicated in different aspects of executive control. The lateral prefrontal cortex is widely recognized as the primary site of cognitive processes associated with the “cold” components of executive functions, i.e., those higher-order abilities that involve planning, problem solving, and voluntary control of behavior in the absence of direct emotional involvement (Chan et al., 2008). According to Milner and Petrides (1984), this region is involved in the management of cognitive flexibility, the temporal organization of events, the regulation of behavior in response to environmental stimuli and the ability to learn from experience. It is particularly active in the planning of sequential actions and the elaboration of goal-oriented strategies (Pennington & Ozonoff, 1996). From a neurofunctional point of view, the lateral PFC operates predominantly according to a “top-down” model, in which processing is guided by the subject's intentions and goals rather than by the salient features of the stimulus, as occurs in “bottom-up” processes. Consequently, lesions to this region impair the ability to inhibit inappropriate automatic responses, as evidenced in Stroop-type

interference tasks (Stroop, 1935). In the presence of damage to the dorsolateral prefrontal cortex, a clinical picture known as the dysexecutive syndrome may manifest itself, characterized by behavioral disorganization, impaired judgement, difficulties in personal care, disturbances in planning, abstract thinking and temporal organization, with a tendency to perseveration (Duffy & Campbell, 1994). Furthermore, complex motor disorders such as aphasia and apraxia may emerge, as well as difficulties in memory monitoring: some patients correctly report a real event, but place it in incongruent temporal or spatial contexts, suggesting a deficit in source monitoring processes (Gilboa & Moscovitch, 2002). Such difficulties are particularly evident in complex planning tasks, as demonstrated by Shallice (1982) through the use of the Tower of London test, which reveals an inability to organize sequences of actions aimed at achieving a goal. The orbitofrontal and medial prefrontal cortex is primarily involved in motivational processes, the evaluation of rewards and punishments, as well as affective regulation and emotional decision-making. Classical studies (Fuster, 1989) have shown that lesions in these two sub-regions result in clinically distinct syndromes: the orbitofrontal syndrome, characterized by euphoria, impulsivity, disinhibition and emotional lability, and the medial syndrome, marked by apathy, abulia, depressed mood and reduced motivation. This distinction was further elaborated by Duffy and Campbell (1994), who identify two main pictures: an uninhibited syndrome, associated with orbitofrontal damage, with symptoms such as reduced social insight, aggressive behavior, hyperreactivity and acquired sociopathy (Damasio, 1994), and an apathetic syndrome, due to lesions of the medial region and connections with the cingulate cortex and supplementary motor area, manifesting as mutism, akinesia, loss of spontaneous prosody and incontinence. According to Ladavas and Berti (2014), patients with orbitofrontal lesions are impaired in economic decisions, i.e. in choices involving the representation and evaluation of alternatives, with attribution of value. Such deficits have been interpreted, in Bechara, Damasio, Tranel and Damasio's (1997) "somatic markers" model, as resulting from the inability to associate somatic (emotional) reactions with specific decision-making options. In the absence of such markers, the subject is theoretically able to reason about the pros and cons of different choices but does so in a cold and affectively meaningless manner, rendering behavioral guidance in complex social and moral contexts inadequate.

In light of the functional complexity and neural distribution of executive functions that emerged in this paragraph, it is evident how EFs constitute a dynamic, adaptive and integrated system capable of orchestrating human behavior in environments of high variability and cognitive

demand. Precisely because of these characteristics, cognitive and action neuroscience has paid increasing attention to the study of EFs in real performance contexts, including sport, where these abilities are constantly put to the test under conditions of time pressure, decision ambiguity and the need for self-regulation. In fact, sport represents an ecologically valid context in which EFs are not only intensively and dynamically solicited, but are also predictive of motor, tactical and decision-making success. Particularly in sports with an open-skill component, where rapid adaptation to changing external stimuli is essential, skills such as inhibition, cognitive flexibility, anticipation and action monitoring emerge as central resources. This growing evidence has led to an important convergence between cognitive and motor sciences, opening up new lines of research aimed at understanding the contribution of EFs to athletic performance and developing neurocognitive enhancement tools specific to the sport context.

1.2 Executive Function in Competitive Sport

The interest in analyzing the influence of EFs on competitive sports performance reaches its peak in conditions of high unpredictability and strong emotional involvement, i.e., when the final result depends on the athlete's ability to express his or her skills to the maximum, in contexts of high psychophysical pressure. Emblematic examples include the decisive penalty in a football elimination round, a free throw to win a basketball match in overtime, or a cricket batsman attempting to reach his first century of runs on the score of 99. In these scenarios, the focus shifts from technical skills in the strict sense to the athlete's psychological competence, which is crucial for maintaining lucidity and motor control under stress (Araujo et al., 2020). In this context, the specific investigation of the relationship between executive functions and sport performance requires a primary focus on how the emotional content experienced by the athlete fits into this link. In this regard, numerous evidence indicates that emotions play a crucial role in regulating the behaviors that constitute sports performance (Vallerand & Blanchard, 2000), significantly influencing not only the outcome of performance but also learning processes. Successful sports performance, in fact, requires continuous adaptation to rapidly changing environmental and situational constraints, often accompanied by intense emotional states. Suppressing or ignoring the influence of emotions would therefore risk disrupting the natural adaptation process between the individual and the environment, preventing the athlete from exploring personal and stable solutions to the task (Davids et al., 2003; Seifert & Davids, 2012). From this perspective, the ecological

dynamical approach proposes an integrated and functional view, according to which traditionally distinct functions such as cognition, emotion, perception and action are not located exclusively in the brain but emerge from the dynamic relationship between organism and environment (Jarvilehto, 1998; Turvey, 2009). In this perspective, past experiences, especially effectively relevant ones, influence the way the individual approaches new tasks, and vice versa, each learning process modifies the dynamic emotion-cognition-action pattern that characterizes the subject (Lewis, 2000, 2004). Such cyclic and continuous interactions form the basis of self-organization, whereby cognition, emotion and action are stabilized in attractor states, i.e. recurring functional configurations that guide adaptive behavior in specific performance contexts (Kelso, 1995). Thus, emotion is not merely an accessory variable but represents a functional constraint that actively structures the exploration and selection of affordances available in a given learning environment (Jones, 2003; Rietveld & Kiverstein, 2014). It has been shown that exposure to high-pressure contexts can impair performance through the phenomena of distraction, loss of attentional focus or excessive awareness and control of motor gestures (Otten & Barrett, 2013). A 109-year longitudinal analysis of batting and pitching statistics in baseball showed a significant drop in performance during play-off games, compared to regular season games, confirming the deleterious effect of high emotional impact situations. Of course, these aggregate results do not exhaust individual variability in responding to pressure: indeed, an athlete's behavior is constructed in the dynamic and contingent interaction between task goals, environmental constraints and personal characteristics (Kelso, 1995; Seifert & Davids, 2012). In this perspective, sport performance is the emergent result of temporal patterns of emotions, perceptions, executive functioning, and actions, constantly shaped by the interaction between external events and internal dynamics of the body-cognitive system (Araújo et al., 2006; Warren, 2006; Vallacher, Van Geert, & Nowak, 2015). In light of these dynamics, it becomes increasingly evident that the athlete's ability to self-regulate under pressure is not only dependent on emotional resilience but is also fundamentally rooted in executive functioning (Vestberg et al., 2012; Jacobson & Matthaeus, 2014). Among the various facets of this complex construct, particular attention has been given to the so-called core executive functions (Diamond, 2013; Sakamoto et al., 2018), which include inhibitory control, working memory, decision-making and cognitive flexibility. These three interrelated components form the cognitive infrastructure that supports goal-directed behavior, attentional regulation, adaptive decision-making, and the coordination of complex motor responses in dynamic contexts (Miyake

et al., 2000; Alvarez & Emory, 2006). In sport, where athletes are constantly required to inhibit automatic responses, update environmental information in real time, and shift strategies according to game demands, the relevance of these core functions is substantial (Voss et al., 2010; Verburgh et al., 2014). Inhibitory control allows for the suppression of impulsive actions that may be counterproductive under pressure (Diamond, 2013; Montuori et al., 2019). Working memory enables athletes to retain and manipulate tactical information while remaining attuned to contextual cues (Vestberg et al., 2017). Cognitive flexibility supports the ability to adapt behavior in response to unexpected changes or opponent actions, a feature especially critical in open-skill disciplines (Vestberg et al., 2017). Given these properties, core executive functions are increasingly being studied as key neurocognitive predictors of athletic performance, especially in competitive settings where cognitive load, emotional arousal, and motor coordination must be integrated in real time (Moreau & Conway, 2013; Faubert & Sidebottom, 2012). The following section will explore the empirical evidence supporting this relationship and discuss how individual differences in EF functioning could explain performance variability across sports, skill levels, and situational demands.

1.2.1 Inhibitory Control

Inhibitory control consists of the voluntary cognitive and/or motor suppression of context-inappropriate responses, accompanied by the ability to maintain a flexible and goal-oriented attentional focus, even in changing environments (Ishihara et al., 2018). Although it has similarities with other self-regulatory mechanisms, such as self-control, a relevant theoretical distinction between these two constructs has been highlighted in the literature (Wennerhold & Friese, 2020). Specifically, whereas self-control refers to general behavioral tendencies that reflect the availability of self-reflexive resources in a variety of contexts, inhibitory control is usually measured through specific tasks that assess an individual's maximal performance under controlled and bounded conditions (Wennerhold & Friese, 2020). Even outside of sport, these two processes have been shown to reflect distinct cognitive mechanisms on a functional and processual level (Scherbaum et al., 2018). The interest in inhibitory control in sport stems from its hypothesized function in suppressing automatic motor responses in highly dynamic environments, such as football, where the ability to promptly block an inappropriate action is crucial for successful decision-making (Verburgh et al., 2014). To measure this ability, experimental paradigms such as

the Stroop color-naming task (Stroop, 1935), the Go/No-Go task, and the Stop-Signal Task itself (Logan et al., 1984) are commonly employed. In support of the discriminative validity of these instruments, recent studies have shown that competitive tennis players perform significantly better on Stroop tasks than non-athletes, suggesting a higher level of inhibitory control in experienced subjects (Pacesova et al., 2018). Moreover, an elevated level of inhibitory control has been associated with an increased likelihood of sporting success, as it represents an essential resource for rapidly adapting to new or changing situations, which characterize the complexity of the competitive sporting environment, as is the case for example in football (Verburgh et al., 2014). In recent years, scientific interest in the study of the relationship between inhibitory control and sport expertise has grown significantly, with numerous contributions highlighting a correlation between these skills and the level of athletic performance (Alves et al., 2013; Verburgh et al., 2014). Specifically, the literature has generally shown that experienced athletes exhibit higher levels of inhibitory control than amateur athlete groups (Jacobson & Matthaeus, 2014). Several studies based on the use of the Stop-Signal Task (SST) have shown that volleyball players scored higher than non-athletes (Alves et al., 2013), that elite youth football players exhibit superior performance compared to amateur peers (Verburgh et al., 2014), and that experienced volleyball players outperform lower-level athletes belonging to badminton in inhibitory control (Meng et al., 2019). Similarly, research focusing on combat sports athletes, Brevers et al. (2018), using a modified version of the SST, found that elite fencers and taekwondo practitioners manifested both proactive inhibitory controls, i.e., the ability to inhibit preemptively in anticipation of a stop stimulus, and reactive i.e., the effective interruption of an action already in progress. Both forms are more developed than in non-athletes. Finally, Nakamoto and Mori (2012) showed that professional baseball players make fewer errors under conditions of sudden changes in ball trajectory, demonstrating greater task-specific inhibitory flexibility than less experienced players. These results support the hypothesis that inhibitory control is not only more efficient in experienced athletes, but that it is specifically adapted to the contextual demands of the sport played.

1.2.2 Working Memory

Higher order cognitive functions like working memory and attention are crucial for athletic performance, according to research (Furley & Wood, 2016; Vestberg et al., 2017). In line with

attentional-control theory (i.e. coordination of attentional resources; Eysenck, Derakshan, Santos, & Calvo, 2007), working memory—the capacity to store and mentally manipulate information—is a key component of executive function and may govern shifting (i.e., the ability to move attention) and inhibition (i.e., the ability to withhold a dominant response; see Miyake et al., 2000). It is important to distinguish between working memory's two primary components, working memory-control and working memory-capacity (see Baddeley, 2003). While working-memory-capacity refers to the storage of information while in transit (e.g., the amount of information that can be handled as described by the episodic buffer; Engle, 2002), working-memory-control refers to the manipulation of information as defined by the central executive in charge of processes like updating (e.g., manipulating incoming information and replacing old information; Miyake et al., 2000). Furthermore, working memory capacity has been employed as a gauge of regulated attention, serving as a stand-in for the episodic buffer (Furley & Memmert, 2012). Although the executive control function (e.g., responsible for coding the most pertinent information; Vestberg et al., 2017) will influence sport performance to some extent, the capacity component is also crucial (e.g., facilitates the amount of information possible for processing; Furley & Wood, 2016). According to research, working memory capacity and sport-based performance tasks are positively correlated; that is, higher working memory capacity is positively correlated with athletic performance (Wood, Vine, & Wilson, 2016). For instance, Buszard, Farrow, Zhu, and Masters (2016) found that while greater visuospatial working memory capacity is linked to more implicit processes, larger verbal working memory capacity is linked to a greater propensity to use explicit processes during a novel tennis hitting task. Moreover, experimental work with athletes attests to the importance of working-memory-capacity in tactical decision-making in professional and semi-professional athletes which is reliant on controlled attention (Furley & Memmert, 2012). In these view, Vaughan and Laborde (2021) highlighted that: (1) attention and working memory measures correlate positively, which may be linked to the fact that both activate the prefrontal cortex and anterior cingulate cortex, suggesting similar underlying neural mechanisms (Yogev-Seligmann et al., 2008) and (2) these measures are also correlated positively with performance. This evidence may illustrate the positive association between cognitive and athletic expertise (Vaughan et al., 2019). Such findings align to recent research highlighting the importance of working-memory-capacity, suggesting that it may interact with other processes explaining associations with athletic

expertise (Buszard et al., 2017; Buszard & Masters, 2018). Furthermore, working memory capacity and expertise may be correlated in a way that improves performance (Buszard et al., 2017).

1.2.3 Cognitive Flexibility

Cognitive flexibility represents one of the pivotal components of executive functions and is defined as an individual's ability to effectively alter one's attention, cognitive perspective or behavioral strategy in response to environmental changes, goals or operational rules (Diamond, 2013). In sport performance, this function becomes particularly critical in contexts with high situational variability, such as in open-skill sports, in which the athlete is constantly challenged to adapt his or her motor and decision-making behavior as a function of rapidly changing external stimuli (Vestberg et al., 2017; Voss et al., 2010). Numerous empirical evidence shows that high-level athletes exhibit greater cognitive flexibility than amateur or non-athlete subjects, suggesting a predictive role of this ability in the effective management of game dynamics (Verburgh et al., 2014; Jacobson & Matthaeus, 2014). At the neurofunctional level, cognitive flexibility is mainly supported by the dorsolateral prefrontal cortex, a region involved in the processes of updating mental representations and inhibiting response patterns that are no longer appropriate (Miyake et al., 2000; Alvarez & Emory, 2006). In sports such as football, basketball or fencing, the ability to switch quickly from one plan of action to another or to correct a strategic choice on the basis of new perceptual input is often decisive for the outcome of performance. A study by Vestberg and colleagues (2017), conducted on elite young footballers, showed that cognitive flexibility as measured by the Design Fluency Test was significantly associated with objective markers of success in sporting careers, such as number of national team appearances and coach evaluations. Similarly, Moratal et al. (2022) have recently shown that experienced combat sports athletes have faster reaction times and a greater capacity for strategic readjustment than beginners in variable stimulus decision-making tasks. This evidence converges in the hypothesis that cognitive flexibility constitutes a discriminating element of sport expertise, not only because it supports tactical effectiveness and decision-making speed, but also because it enables the athlete to maintain attentional control and behavioral adaptation even under conditions of pressure and uncertainty.

1.2.4 Decision Making

Decision-making represents a central cognitive skill for elite sports performance, as it enables the athlete to quickly and effectively choose between action alternatives in contexts subject to strong

temporal, spatial and social constraints. This process involves both deliberative aspects and forms of expert intuition, the result of situated learning and perceptual-motor integration built over time (Abernethy et al., 2012; Williams & Ericsson, 2005). In open-skill sports, such as football, basketball or rugby, where the environment changes rapidly and unpredictably, speed and decision-making accuracy become crucial (Roca et al., 2011; Hepler & Feltz, 2012). As explored in more detail in the previous sections, the work of Voss et al. (2010) and Vestberg et al. (2012) has shown that higher-level athletes perform better in rapid decision-making and action selection tasks, suggesting a central role of executive functions, in particular cognitive flexibility, inhibition and working memory, in supporting decision-making behavior. Recent neuroscientific research has shown that brain activity associated with decision-making in sport involves fronto-parietal networks and areas related to anticipatory risk assessment and response selection, such as the precuneus, anterior insula and medial prefrontal regions (Hülsdünker et al., 2021; Krumer et al., 2022). In particular, EEG studies have found in experienced soccer players a more efficient modulation of anticipatory and post-stimulus potentials, confirming a faster and more targeted processing of contextual information during decisional critical situations (Di Russo et al., 2017). From a behavioral perspective, Raab and Johnson (2007) propose a distinction between preference-based and rule-based decision-making, depending on whether the choice is based on intuitive heuristics built in practice or on deliberate principles. In experienced athletes, decisions tend to be faster, less verbal and more related to the direct perception of affordances offered by the environment (Travassos et al., 2013), in line with the ecological dynamics approach, which conceives decision-making as an emergent and self-organized behavior, shaped by the constraints of the athlete, the task and the environment (Araújo et al., 2006; Davids et al., 2013). Further research has shown how situational variability during training can enhance decision quality: O'Connor et al. (2018) showed that the systematic inclusion of perceptual and decision-making constraints in reduced games significantly improves response times and the accuracy of tactical choices in footballers. Furthermore, the introduction of dual-task cognitive tasks in simulated contexts (Faubert & Sidebottom, 2012; Romeas et al., 2016) appears to enhance decision-making robustness under conditions of high cognitive pressure. From an application point of view, it is now clear that the quality of decisions is not merely a consequence of experience, but can be trained and evaluated systematically, through neurocognitive protocols, dual task cognitive-motor

training, VR-based tasks and situated learning contexts, with the aim of making decisions increasingly efficient, automated and contextually sensitive.

Chapter 2: Cognitive-Motor Dual-Task (CMDT) Training

2.1 Models and empirical findings

A crucial aspect of human existence is movement. While motor control requires the activation of cognitive processes, it has been hypothesized that movement itself may in turn influence cognition and its underlying mechanisms, including those of a structural nature (Hamacher et al., 2015). As extensively defined in the first chapter, the term cognition refers to a broad and articulated set of mental abilities required to perceive, process and interact adaptively with the surrounding environment (Bostrom & Sandberg, 2009; Borson, 2010). From this perspective, maintaining intact and efficient cognitive processes is a fundamental prerequisite for the individual's adaptive functioning in everyday life and, by extension, in the context of sports and motor performance too. Throughout the lifespan, cognitive performance is subject to numerous influences and variations. The physiological ageing process is generally associated with a decline in cognitive functions, particularly in processing speed and memory (Albert, 1997; Park et al., 2002; Fjell & Walhovd, 2010). With advancing age, there is also an increased risk of developing degenerative neurological diseases, most notably dementia (Fiest et al., 2016). This condition has a strongly negative impact on an individual's cognitive performance, impairing autonomy and significantly reducing quality of life (Andersen et al., 2004; Fiest et al., 2016). Scientific evidence indicates that neuropathological signs of dementia are exacerbated by sedentariness and low physical activity (Scherder et al., 2010). Indeed, sedentary behavior and physical inactivity have been associated with a decline in cognitive function (Falck et al., 2016; Ku et al., 2017) and a consequent increase in social and healthcare costs (Janssen, 2012; Peeters et al., 2014). Unfortunately, in recent decades, there has been a marked increase in the average daily time spent in motor inactivity in Western countries (Owen et al., 2010; Church et al., 2011).

In light of these data, it could be expected that the proportion of individuals with impaired cognitive abilities will increase in the coming years, making the development of effective cognitive enhancement strategies urgent (Colzato, 2016). Such interventions should aim to increase the so-called cognitive reserve defined as the individual difference in the ability to process cognitive tasks (Stern, 2002, 2009) and improve neural resilience to neurodegenerative processes (Nithianantharajah & Hannan, 2009; Stern, 2012, 2013). Two factors have been identified as

crucial for maintaining cognitive function and enhancing cognitive reserve: (I) physical activity, defined as any bodily movement generated by skeletal muscles that results in an energy expenditure greater than ~1.5 MET (Caspersen et al., 1985; Ainsworth et al., 2000; Mansoubi et al., 2015), and (II) structured exercise, which is a planned, repetitive and organized form of physical activity (Caspersen et al., 1985; Budde et al., 2016). Numerous studies have shown that physical activity and exercise can improve cognitive function at all stages of the life cycle: children (Hillman & Schott, 2013; Chaddock-Heyman et al., 2014; Khan & Hillman, 2014; Verburch et al., 2014; Ludyga et al., 2016), adolescents (Esteban-Cornejo et al., 2015; Greeff et al., 2017; Li et al., 2017), young and middle-aged adults (Cox et al., 2016), older adults (Colcombe & Kramer, 2003; Erickson et al., 2013; Northey et al., 2017), and people with neurocognitive disorders, including dementia (Heyn et al., 2004; Smith et al., 2013; Ahn et al., 2017). Such effects have been observed after both acute (single sessions) exercise sessions (Chang et al., 2012; Roig et al., 2013) and chronic (long-term interventions) protocols (Bherer et al., 2013; Hötting & Röder, 2013). Specifically chronic and acute exercises, as long as they have a high cognitive and motor demand, represent a powerful stimulus for the optimization of executive functions and cognitive control. The positive effect exerted by physically demanding exercises on the cognitive level confirms the recommendations proposed by Pesce (2012), who suggests a paradigm shift in research on the interaction between motor exercise and cognition, moving from an approach centered on quantitative parameters (such as duration and intensity) to a greater focus on qualitative aspects, in particular the type of exercise performed. In this sense, it has been hypothesized that the simultaneous combination of exercise and cognitive stimulation - often referred to as dual task cognitive motor training (CMDT) - could generate superior cognitive enhancement compared to interventions conducted in single mode, i.e. purely physical or purely cognitive (Lauenroth et al., 2016; Levin et al., 2017). To understand the benefits of combining exercise and cognitive stimulation, it is useful to refer to our evolutionary history. From an evolutionary point of view, in fact, the human body and its organ systems developed by manifesting a high capacity to adapt to environmental constraints (Raichlen & Alexander, 2017). Over the centuries, human physiology has adapted to an active lifestyle functional to the survival of the species, as evidenced by ancestral activities such as gathering, hunting and fishing (Raichlen & Alexander, 2017). In contrast, the current trend towards sedentary lifestyles in industrialized societies (Owen et al., 2010; Church et al., 2011) seems to have favored dysfunctional adaptations, aimed at minimizing energy

expenditure, but leading to a simultaneous decline in motor and cognitive systems (Raichlen & Alexander, 2017). Indeed, our ancestors' subsistence activities, such as hunting, required the synergetic and simultaneous use of cognitive and sensorimotor resources: walking long distances while carefully observing the environment in search of food, detecting a moving animal and coordinating it with a precise motor gesture such as throwing a spear. These cognitive processes were intrinsically connected with bodily actions and environmental interaction, a concept that comes close to the theories of embodied cognition and embedded cognition, according to which cognition is not separate from the body and context, but emerges from them through interaction (Pouw et al., 2014a, 2014b). Such considerations lead to the conclusion that the integration of physical and cognitive challenges is an essential condition for preserving or enhancing neural capacity, which in turn ensures the efficiency of cognitive processes (Kempermann et al., 2010; Fissler et al., 2013; Bamidis et al., 2014; Raichlen & Alexander, 2017). According to the theoretical model of *guided plasticity facilitation*, the combination of physical exercise and cognitive stimulation produces greater synergistic effects than the sum of the benefits from each type of intervention performed in isolation (Kraft, 2012; Fissler et al., 2013). This super additive effect would emerge from the convergence of two distinct but complementary mechanisms: (I) exercise-induced *facilitation effects* and (II) the *driving effects* produced by cognitive stimulation (Fissler et al., 2013). The facilitation effects are related to the activation of neurophysiological mechanisms that promote neuroplasticity, including the increased production of neurotrophic factors, such as Brain-Derived Neurotrophic Factor (BDNF) (Assis & Almondes, 2017; Dinoff et al., 2017). BDNF is strongly associated with neurogenesis and synaptogenesis, processes that are fundamental for the consolidation of learning and improvement of cognitive function (Brigadski & Leßmann, 2014; Borrer, 2017). Studies have shown an increase in BDNF levels during and up to 60 minutes after acute exercise (Piepmeier & Etnier, 2015; Dinoff et al., 2017), suggesting that such facilitation effects are transient and time-delimited (Fissler et al., 2013).

While acute exercise thus appears to open a temporary window of transient neuroplasticity (Geibig et al., 2012), cognitive stimulation would act as a guide, directing and stabilizing these plastic processes (Fissler et al., 2013; Bamidis et al., 2014). Guidance effects are believed to activate cell survival mechanisms specific to newly formed neurons (Fabel et al., 2009). These mechanisms are part of a complex, multi-step system that requires the functional activation of synapses and newly generated neurons, achieved precisely through the execution of cognitive tasks. Such activation

promotes the structural and functional integration of the new cells within existing brain circuits (Bruehl-Jungerman et al., 2007; Bergami & Berninger, 2012). Integration into functional circuits is therefore essential to stabilize the neuroplastic changes induced by CMDT. Furthermore, alongside plasticity, stabilization of central nervous system structures is also crucial to ensure the maintenance of efficient brain functioning (Kasai et al., 2003; Koleske, 2013). As illustrated in the theoretical model depicted in **Figure 2**, motor and cognitive exercises can be combined in different ways. A first fundamental classification for understanding its effectiveness concerns the temporal order in which these stimuli are proposed within the intervention (Fissler et al., 2013; Frith et al., 2017). Based on this criterion, two main configurations of motor-cognitive training can be distinguished:

- i. sequential (or successive) training, or cognitive motor training (CMT) in which the motor and cognitive components are performed at separate and consecutive times, and
- ii. simultaneous training, dual task cognitive motor training (CMDT), in which physical exercise and cognitive stimulation are performed simultaneously.

This distinction represents a key aspect in the design of combination protocols, as it can significantly influence the extent and quality of the neurocognitive effects that can be achieved.

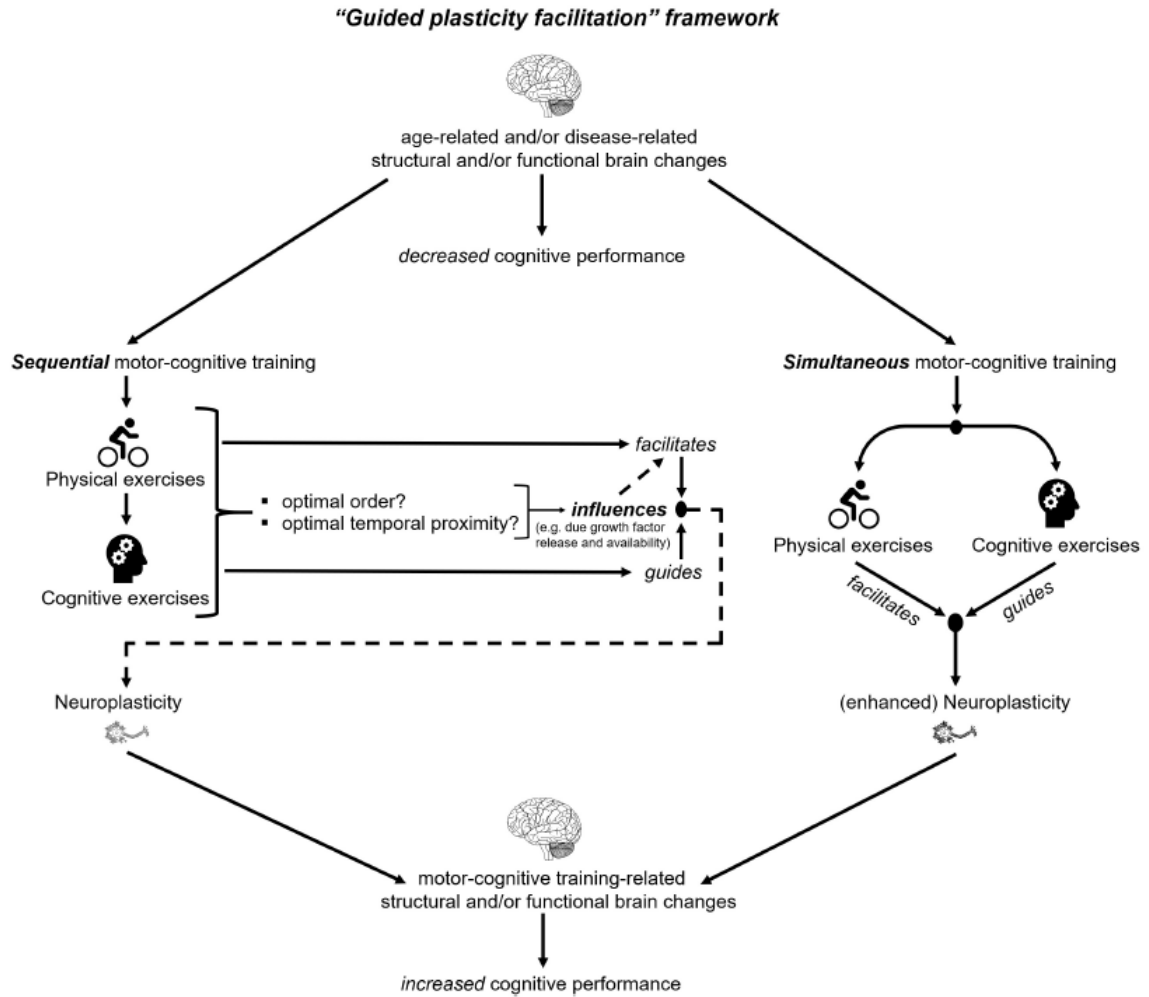


Figure 1. Schematic illustration of the “Guided plasticity facilitation” framework (Herold et al., 2018)

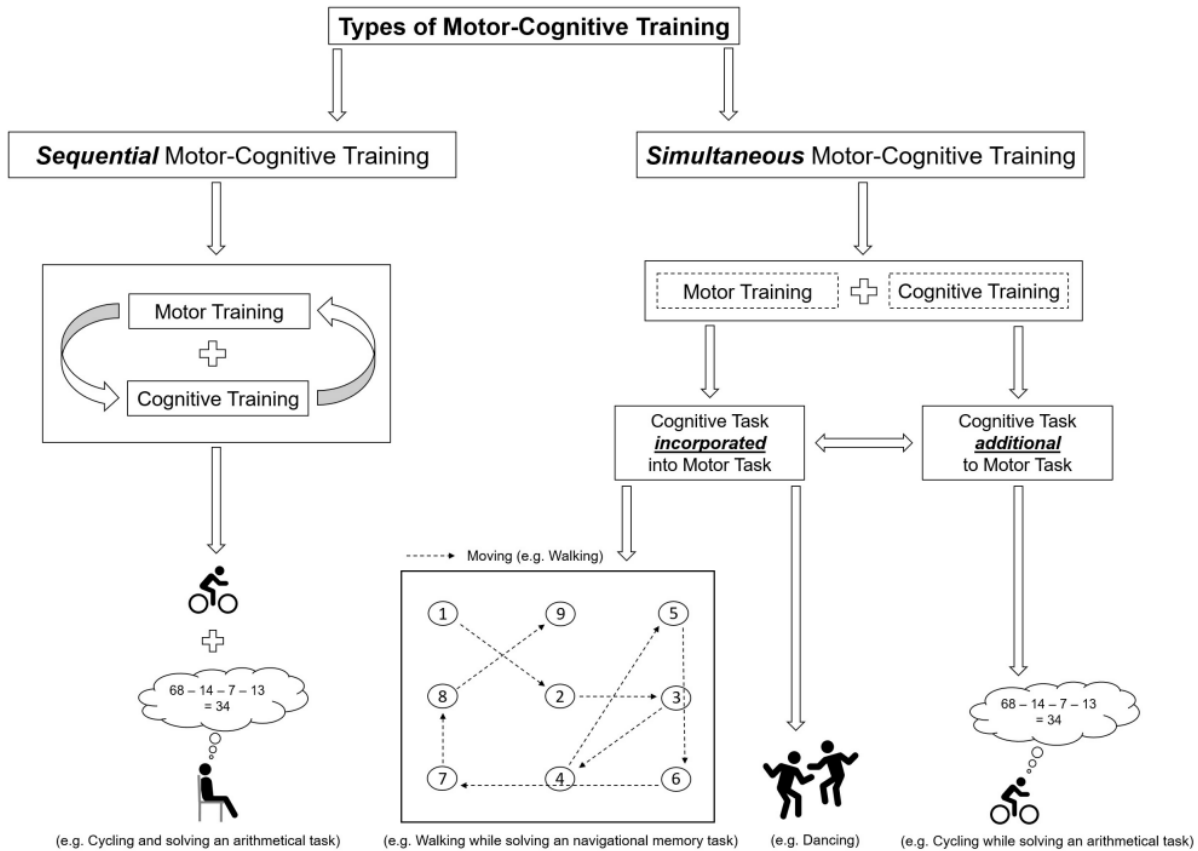


Figure 2. Schematic illustration of the classification of motor-cognitive training and exemplifying illustrations of the differences between “additional” and “incorporated” cognitive training (Herold et al., 2018).

In sequential CMT, motor and cognitive training are performed at separate times, either on the same day (before or after an exercise session) or on separate days (Tait et al., 2017). In this type of approach, the motor component often consists of aerobic, resistance, balance and flexibility exercises or a combination of these (Lauenroth et al., 2016; Tait et al., 2017). An advantage associated with this modality is the lower likelihood of dual-task costs, i.e. performance decrements in the motor task, the cognitive task, or both, due to the simultaneous handling of two activities (Hamacher et al., 2017). In addition, prioritization, effects, i.e., an individual tendency to prioritize one of the two tasks, are less likely to occur, a factor that may influence intervention outcomes.

However, one of the main criticisms of sequential training lies in the lack of clear knowledge about the optimal loading characteristics (frequency, duration, type of exercise and temporal order

between motor and cognitive stimulation) required to achieve favorable cognitive effects (Lauenroth et al., 2016). Some evidence suggests that maximum cognitive benefits are observed when cognitive training is performed 11-20 minutes after an acute exercise session (Chang et al., 2012), while other studies report improved performance when exercise is performed four hours after learning, rather than immediately (van Dongen et al., 2016). Consequently, it is still unclear whether cognitive stimulation should precede or follow motor activity. A recent review comparing the effects of sequential and simultaneous training showed that simultaneous training produces more significant cognitive improvements in different populations, whereas the results of sequential training are inconclusive to date (Tait et al., 2017). This discrepancy could depend on the uncertainty regarding the best time interval between motor and cognitive stimulation, as different timing can activate different neurobiological pathways (Tait et al., 2017). In light of these results, simultaneous CMDT appears to be a more promising and time-efficient approach for enhancing cognitive function. This type of training can be further classified according to the type of cognitive demand involved in the task (Herold et al., 2018). According to this classification, two main modalities can be distinguished. The first concerns cognitive-motor training with an additional cognitive task, which can be assimilated to the classical dual-task approach, in which the cognitive task functions as a distractor to the motor task (Schott, 2015). In this case, the cognitive task is not relevant to the performance of the motor task (non-relevant task), such as walking while solving arithmetic operations or pedaling on an exercise bike while listing alternating letters. This mode could be described as *thinking while moving*. The second mode occurs when the cognitive task is incorporated into the motor task, becoming a necessary condition for its successful execution (Schott, 2015). In this case, the cognitive task is relevant to the success of the task (task relevant), for example, in walking towards cones arranged in a specific order, or in dance, where the motor sequence is linked to a procedural or spatial memory. This approach can be defined as *moving while thinking*. According to the authors, incorporating the cognitive task into the motor task is more advantageous in terms of stabilizing neuroplasticity effects than using the cognitive task as a simple distractor. The reasons supporting this thesis are manifold: (I) several studies suggest that integrating the cognitive task into the motor task produces a synergistic effect between cognitive and motor stimuli, with more significant improvements on both the cognitive and motor level (Moreau & Conway, 2013; Moreau, 2015; Ruiter et al., 2015). For example, it has been observed that integrating the cognitive component during physical activity improves learning in children to

a greater extent than motor activity not associated with any cognitive task (Mavilidi et al., 2016, 2017, 2018). (II) A training format that incorporates the cognitive task into the motor task better reflects everyday life situations. It is unlikely, for example, that an elderly person would solve arithmetic exercises during a walk, whereas it is much more realistic for them to walk through a supermarket mentally remembering which products to buy and where to find them. These findings suggest that the ecological and functional relevance of concurrent training with integrated tasks could represent a fundamental key to maximizing the adaptive potential of CMDT, in terms of both cognitive efficacy and transferability to real-life scenarios. (2a) The benefits of exercise are modulated by expectations (i.e., beliefs about the efficacy of the intervention) and individual preferences (Crum & Langer, 2007; Helfer et al., 2015). Since also neurophysiological parameters are influenced by preferences and expectations towards exercise (Schneider et al., 2009; Mothes et al., 2016), it could be reasonably assumed that also the neuronal adaptation processes induced by exercise and the resulting cognitive outcomes are subject to such modulations. A relevant example is represented by the rate of adherence to intervention, which is crucial for its effectiveness and depends largely on the subjective perception of the significance of the activity with respect to one's personal condition (Fissler et al., 2013; Lautenschlager & Cox, 2013). Since a cognitive task embedded in a motor activity reflects situations of daily life, it is likely to be perceived as meaningful and, consequently, to favor greater adherence and success of the training. (2b) Older adults (Park et al., 2002) and people with dementia (Pal et al., 2016) commonly show difficulties in visuospatial skills, such as remembering the location of a product in the supermarket. Considering that physical fitness is able to improve cognitive functions (Carvalho et al., 2014; Groot et al., 2016), an effective intervention on this type of deficit should include both cognitive exercises and physical activity. Furthermore, since brain adaptations are task-specific (Green & Bavelier, 2012; Schlaffke et al., 2014), it is proposed that the ideal intervention should also be task-specific, for example related to spatial memory, in order to generate transfer effects not only towards daily cognitive functions (such as remembering the shopping list), but also towards activities of daily living (such as walking) (Jobe et al., 2001; Zelinski, 2009). These considerations suggest that the cognitive task should be integrated into the motor task. In the supermarket example, remembering and moving towards the desired products represents a joint action between memory and locomotion. This approach is schematically represented in **Figure 2**. (III) If the cognitive task is integrated into the motor task, prioritization effects, often observed in dual-task

tasks with additional stimuli, do not occur (Yogev-Seligmann et al., 2012a; Plummer et al., 2013, 2014; Plummer & Eskes, 2015). Such effects, which consist in prioritizing either the cognitive or the motor task, are known to negatively affect both motor and cognitive performance (Yogev-Seligmann et al., 2012b; Plummer et al., 2015a, 2015b), as well as the activation of prefrontal structures (Lague-Beauvais et al., 2015). In theoretical terms, these effects could induce unwanted adaptation processes. (IV) A further advantage of CMDT is the simultaneous stimulation of multiple sensory systems, since the execution and control of the two types of activities occur simultaneously. It is also hypothesized that multisensory training environments more closely mirror real-life conditions, thus being more ecologically valid and more effective in promoting complex cognitive processes such as learning (Shams & Seitz, 2008). In addition to realistic scenarios, such as the supermarket, virtual reality environments also offer the possibility of combining cognitive and motor tasks without the need to build complex physical environments (Tarr & Warren, 2002; Bruin et al., 2010). An example of such approaches is represented by exergames (Skjæret et al., 2016; Boissieu et al., 2017), video games that include physical exercise components and that, within our framework, can be classified as CMDT, as they jointly solicit cognitive and motor skills (Pichierri et al., 2012; Monteiro-Junior et al., 2016). Given the wide relevance and influence of CMDT on brain plasticity processes in favor of cognitive and motor performance, in recent years the literature has focused on the possible beneficial factors offered by this training practice in the context of sports performance. In open-skill sports, characterized by high unpredictability, changeability and high decisional demand, the integration between cognitive function training and motor skills could be crucial for the success of the performance. In this context, CMDT would be a highly effective approach to simultaneously optimize physical and cognitive abilities. Several studies have shown that the inclusion of cognitive components within multi-component protocols (MCT) allows not only to improve sprint and agility, but also to enhance decisional reaction time (Lucia et al., 2023). These improvements have been associated with a greater amplitude of the Event-Related Potentials (ERP) P3 component, indicative of a more efficient post-perceptual and decisional processing. In parallel, it has been observed that the integration of such protocols during sport-specific technical exercises would lead to an increase in anticipatory neural activity in frontal regions, increasing the amplitude of prefrontal negativity (pN) and Bereitschaftspotential (BP), neural markers of proactive inhibition and motor preparation respectively (Lucia et al., 2022). These data suggest and confirm that CMDT would stimulate,

even in the sports context, processes of reactive and proactive neuroplasticity, functional to sports performance. Not only did the implementation of these protocols led to an improvement in specific metrics of technical performance (e.g., time in dribbling tests), but it also proved to be more effective than standard training in short periods (5 weeks), in modulating the brain dynamics underlying rapid decision making, visual speed and attention capacity. The systematic inclusion of CMDT in training sessions therefore represents an evidence-based strategy for the joint optimization of motor and cognitive performance in elite athletes. In summary, current theoretical and empirical evidence converges in indicating simultaneous motor-cognitive training (CMDT) as one of the most promising strategies to support and enhance cognitive functions in distinct phases of the life cycle. The synergistic combination of motor and cognitive stimuli, especially when integrated in ecologically valid and functional contexts for daily life, seems to constitute a powerful catalyst for the induction and stabilization of neurocognitive plasticity. However, despite the growing theoretical validation, the concrete implementation of such protocols requires tools capable of reproducing dynamic, controllable and adaptable environments to the individual subject. In this scenario, virtual reality (VR) emerges as a technology particularly suited to support the application and study of CMDT, offering immersive, precise and customizable solutions for neurocognitive training. The next section will therefore explore how VR can represent a valid operational and experimental tool for the development and administration of evidence-based CMDT interventions.

2.2 Virtual Reality (VR) as a Tool for CMDT

Virtual reality (VR) is one of the emerging technologies capable of attracting ever-increasing attention and widespread recognition of its benefits and potential practical applications in various sectors. In the medical field, for example, Tiffany & Fornierns (2018) had predicted a significant expansion rate of this technology, of approximately 35%. (Tiffany & Forneris, 2018). This data underlines the growing importance of VR not only as an innovative learning tool, but also as a technology that is rapidly gaining more and more space, becoming more accessible to the public due to technological progress, leading to many applications such as entertainment (Atkinson et al., 2020), interactive training (Claude et al., 2014; Bouville et al., 2015; Casella et al., 2024), scientific visualization (Chandler et al., 2015; Dwyer et al., 2018; Iosa et al., 2021), and virtual therapy (Donker et al., 2019; Lindner, 2020). However, despite the excitement surrounding this

technology, there is still some confusion about what exactly constitutes VR, which is why it is crucial to clarify definitions (Kardong-Edgren et al., 2019). Definitions of VR in literature are numerous and often divergent. This lack of terminological consistency highlights the need for greater standardization in describing what exactly VR is, especially in a historical period in which the vocabulary related to these technologies is constantly evolving and expanding (Cant et al. 2019; Steuer, J. 1992). Having a clear and shared definition is essential not only to facilitate the understanding and use of VR, but also to ensure that technological development and scientific research can advance more effectively, based on more accurate and informed user feedback. This is especially important as VR adoption is spreading in increasingly diverse contexts, from healthcare to education, entertainment and industry (Kardong-Edgren et al., 2019). One of the most common definitions of VR is the one that describes it as: "the use of computer technology to create an interactive three-dimensional world in which objects have a spatial presence". In this description, VR is considered as a digitally created environment, in which objects are not simple two-dimensional images on a screen, but appear with depth and physicality that seem real. This ability to create interactive three-dimensional environments makes VR particularly suitable for providing immersive experiences, where the user can explore and interact with a digital environment in a completely natural way. Furthermore, terms such as "virtual environment" and "virtual world" are often used interchangeably to refer to these digital spaces that imitate physical reality (Department of Defense, 2018). Virtual reality can therefore be described as an interactive simulation generated by a computer, capable of transmitting sensory information to a user who interprets it as modified or enhanced compared to reality (Abari et al. 2017). This technology offers users the possibility of feeling completely immersed in an artificially created scenario (embodiment), giving the impression that what they see, hear or touch is part of the real world. In this way, it is essential to understand the sense of embodiment (SoE), "*the subjective experience of using and having a body*" (Blanke and Metzinger, 2009)] in VR applications. Multiple communities study the SoE in their own way (Longo et al., 2008; Blanke and Metzinger, 2009; de Vignemont, 2011; Kilteni et al., 2012). Based on the nomenclature proposed by Kilteni et al. (2012a), which is widely acknowledged in the VR community, we define the SoE as the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body, especially in relation to virtual reality applications. The SoE is characterized by three sub-components, defined as follows (Kilteni et al., 2012a). The sense of agency (SoA) is the feeling of being the

cause of our actions. The sense of body ownership (SoBO) is the feeling that the virtual body is the source of our sensations (like our real body). Finally, the sense of self-location (SoSL) is the spatial experience of being inside a body. Currently, this level of immersion can be achieved through different sensory channels: sight, using special viewers or virtual reality glasses that project three-dimensional images; touch, through the use of devices such as haptic gloves, which allow the perception of the physical sensation of touching or manipulating objects in the virtual world; and hearing, through the use of headphones that transmit realistic sounds, further increasing the sensation of being present in the simulated environment (Fernandez, 2017). From a purely neuroscientific point of view, the neurocognitive model of SoBO, in which the SoBO is based on pre-existing internal body maps and is integrated from different information sources (Tsakiris, 2010), effectively explains how it is possible for the user to perceive a perfect sense of immersion within the virtual environment. This neurocognitive model is a comparator model of the SoBO working with three levels: the first level opposes the visual appearance of an observed object to a pre-existing, temporally stable body model; on the second level, the current body schema state is compared to the anatomical, structural, and postural features of the observed object; and finally, the different sensory information about the observed object is matched in the third level, to give rise to a SoBO if coherent. This neurocognitive model processes each level successively. If there are enough similarities, the second level is processed until the third and last level (Armel and Ramachandran, 2003; Tsakiris and Haggard, 2005; Tsakiris et al., 2010). This ability to fool the senses and make the brain believe that what is being experienced is actually real distinguishes VR from other forms of human-computer interaction, where the user always remains aware of the technological fiction (Slater & Sanchez-Vives 2016). This aspect is what makes this technology particularly powerful in contexts where deep immersion is required, such as in education, therapy or entertainment. VR, therefore, is considered an independent and autonomous technology, capable of offering experiences that would not be possible in other technological modalities and the innovations developed for this technology are in fact finding applications in a wide range of sectors. For example, in the gaming industry, VR allows players to fully immerse themselves in virtual worlds, while in the education sector, it allows students to practice and learn in highly realistic simulated environments, in the medical field it allows to simulate surgical operations or for the rehabilitation of patients. Therefore, in light of its numerous intrinsic characteristics of controllability, manipulation, and management of the virtual environment, VR represents today

one of the most promising tools for the advanced implementation of CMDT protocols, through the possibility of manipulating, controlling and dynamically adapting the training environment. Unlike traditional tools (e.g., LED lights, photocells, manual buttons), VR would allow the generation of immersive, multisensory and sport-specific contexts (Richlan, 2025), which promote highly ecological cognitive-motor stimulation, while maintaining an important level of experimental control. One of the most relevant aspects is the possibility of voluntarily and precisely altering environmental parameters (e.g., number and speed of stimuli, opponent trajectories, presence of distractors, available decision-making time), adapting them to the athlete's level and training objectives. This degree of control represents a structural enhancement of the CMDT, since it allows the fine modulation of cognitive and motor difficulty, facilitating the principle of progressive cognitive overload and promoting neuroplasticity in a targeted way. Furthermore, the immersive nature of VR allows for the elimination of the gap between stimulus and context: cognitive stimuli (e.g., moving opponents, ball trajectories, contextual visual cues) are no longer artificial or disconnected from the reality of the match but are an integral part of the environment itself. This aspect is particularly relevant in light of theories on mirror neurons and embodied cognition, which suggest that observation and interaction with stimuli with motor meaning and situational context increase the activity of premotor areas and improve learning by simulation. In this perspective, VR would allow the structuring of dual tasks in which motor action is directed towards real and significant objectives (e.g., intercepting a pass, anticipating a dribble), improving the transferability of training to the real field. The possibility of reproducing complex and dynamic environments also allows the continuous training of key executive functions such as inhibition, memory updating and cognitive flexibility, in a situated training format that reflects the conditions of pressure and uncertainty typical of sports competition. In summary, Virtual Reality does not only represent an alternative modality to deliver CMDT but could introduce a paradigm shift in the integrated stimulation of cognitive and motor functions, providing an adaptable, immersive and contextual environment, capable of maximizing learning processes, accelerating their speed and improving their transferability.

2.3 Neural Evidence on VR-Induced Plasticity

Given the above and in accordance with some scientific evidence, VR would represent an ideal technology for increasing brain neuroplasticity, enhancing cognitive-motor abilities and promoting

the health status of the individual. Specifically, immersing users in interactive virtual environments allows them to provide targeted cognitive stimulation, promote neural adaptation and facilitate the acquisition of new skills (Brown et al., 2023). To date, numerous research in the clinical setting have confirmed the countless benefits offered by this technology, as the immersive nature of VR allows for the delivery of personalized and adaptive interventions tailored to individual cognitive profiles and therapeutic goals (Enriquez-Geppert et al., 2018). Virtual reality environments offer a safe and controlled setting for practicing activities of daily living, motor tasks, and cognitive exercises, enabling patients to relearn skills and regain independence. Following a neurological illness or damage, cognitive rehabilitation is one of the most attractive uses of virtual reality. VR-based therapies intended to encourage neuroplasticity and support functional recovery can be extremely beneficial for people with neurodegenerative diseases including Alzheimer's disease, stroke survivors, and traumatic brain injury (TBI) patients (Tanaka et al., 2023). Additionally, VR-based cognitive training programs have been created especially to target cognitive domains including memory, attention, and executive function that are impacted by aging or neurological diseases (Cheng et al., 2020). By putting users through mental exercises and cognitive challenges in immersive virtual settings, these programs encourage synaptic plasticity and neural activity in pertinent brain regions. Studies show that VR cognitive training could enhance cognitive abilities like problem-solving, attentional control, and memory recall (Biasucci et al., 2018). Specifically, a VR-based cognitive training for people with mild cognitive impairment (MCI) was carried out by Manera et al. (2020). Their results showed that participants in VR workouts aimed at memory, attention, and executive skills significantly improved their cognitive function and everyday life activities. Garrett et al. (2021) investigated VR as a non-pharmacological intervention for chronic pain management. Their study demonstrated that immersive VR experiences effectively reduced pain intensity and improved pain-related outcomes such as mood and quality of life in patients with chronic pain conditions. Prasad et al. (2020) used virtual reality (VR) and brain-computer interface (BCI) technology in the field of motor rehabilitation to support upper limb rehabilitation following a stroke. When compared to traditional rehabilitation techniques, stroke patients who used the VR-BCI system demonstrated improved motor recovery and functional benefits. The BCI's real-time neurofeedback enabled neuroplastic alterations that enhanced motor control and self-reliance. In addition, Aizawa et al. (2021) explored the use of VR-based interventions for improving cognitive functions in individuals with Alzheimer's disease. Their randomized

controlled trial demonstrated significant enhancements in memory recall and executive function among Alzheimer's patients who engaged in VR cognitive training compared to controls. The study highlighted VR's potential to stimulate neural activation and promote cognitive recovery in neurodegenerative conditions. Non solo, anche da un punto di vista motorio, nell'ambito clinico, sono emersi numerosi benefici a seguito di specifici programmi VR. In order to facilitate upper limb rehabilitation following a stroke, Prasad et al. (2020) combined virtual reality (VR) with brain-computer interface (BCI) technology. When compared to traditional rehabilitation techniques, stroke patients who used the VR-BCI system demonstrated improved motor recovery and functional benefits. The BCI's real-time neurofeedback enabled neuroplastic alterations that enhanced motor control and self-reliance. Recent work by Santos et al. (2023) has demonstrated the feasibility and efficacy of VR-based interventions for improving balance and gait in individuals with Parkinson's disease. By simulating challenging environments and providing real-time feedback, VR helps patients practice motor tasks in a safe and controlled manner, promoting neuroplasticity and functional recovery. So, considering VR's ability to create immersive and controlled environments and given the many cognitive-motor benefits offered by such technology in the clinical setting, some researchers have explored the possible neuroplastic effects offered by VR in the field of athletic performance enhancement. Richlan (2025), following sport-specific VR-based training focused on headshots in the game of football showed, in addition to a significant increase in motor and behavioral skills, an interesting neuroplasticity effect. The comparison of the gray matter (GM) images, **Figure 3**, revealed an increase in GM volume in the left thalamus. In addition, the comparison of the white matter (WM) images revealed an increase in WM volume in the bilateral cerebellum. In both regions, and in line with the behavioral findings, the signal intensity values show a continuous increase from T0 (pre-intervention) to T4 (post-intervention) with a stable retention effect after four weeks without training (T8). Furthermore, the analysis of the cortical thickness images showed an increase in cortical thickness from T0 to T4 in the right insula, left inferior temporal gyrus, left Parahippocampal gyrus, left lingual gyrus, left posterior cingulate cortex, and bilateral anterior cingulate and medial prefrontal cortex. The seed-based correlation analyses of the resting-state fMRI data revealed manifold increases in functional connectivity within and between important brain networks. Similarly, in a study by Casella et al. (2024), following a specific virtual reality reaction training protocol (VRRT) conducted on a general population of young adult athletes, it was found that the group subjected to VRRT not only

reported a significant increase in behavioral responses and motor reaction test, but also showed a significant increase in anticipatory ERP Bereitschaftspotential (BP) component. This component, in accordance with long-standing studies, would clearly reflect the human being's motor preparation activity. Thus, even in this case VR demonstrated beneficial effects in modulating brain plasticity and specific motor skills. In this view, Grooms et al. (2018) provided highly relevant preliminary evidence on the neuroplastic mechanisms that support the transfer of neuromuscular adaptations from training to actual sports performance. The study showed that a neuromuscular training protocol enhanced by real-time visual feedback induces significant modifications in brain activity, particularly in motor, visuospatial and movement planning systems. These modifications were found to be strongly correlated with improved biomechanics during sport-specific tasks in virtual reality. These results are consistent with the principle of neural efficiency according to which, following motor learning, the execution of complex motor tasks requires less cortical activation due to the involvement of more automatic and subcortical circuits. Such efficiency allows the motor system to free up cortical resources to be allocated to more complex tasks such as sensory regulation and response to unpredictable environmental stimuli, characteristic of sports performance. From an applicative point of view, the data suggests that certain neuroplastic modifications can be directed through training strategies that stress sensory and visuospatial integration. This implies the use of tools such as dual-tasking, virtual reality training, and/or the synergy between CMDT and VR. The fact that these results were obtained in an immersive VR scenario further confirms the effectiveness of sport-specific virtual environments as valid tools to monitor, stimulate and transfer motor learning under conditions of high ecological validity.

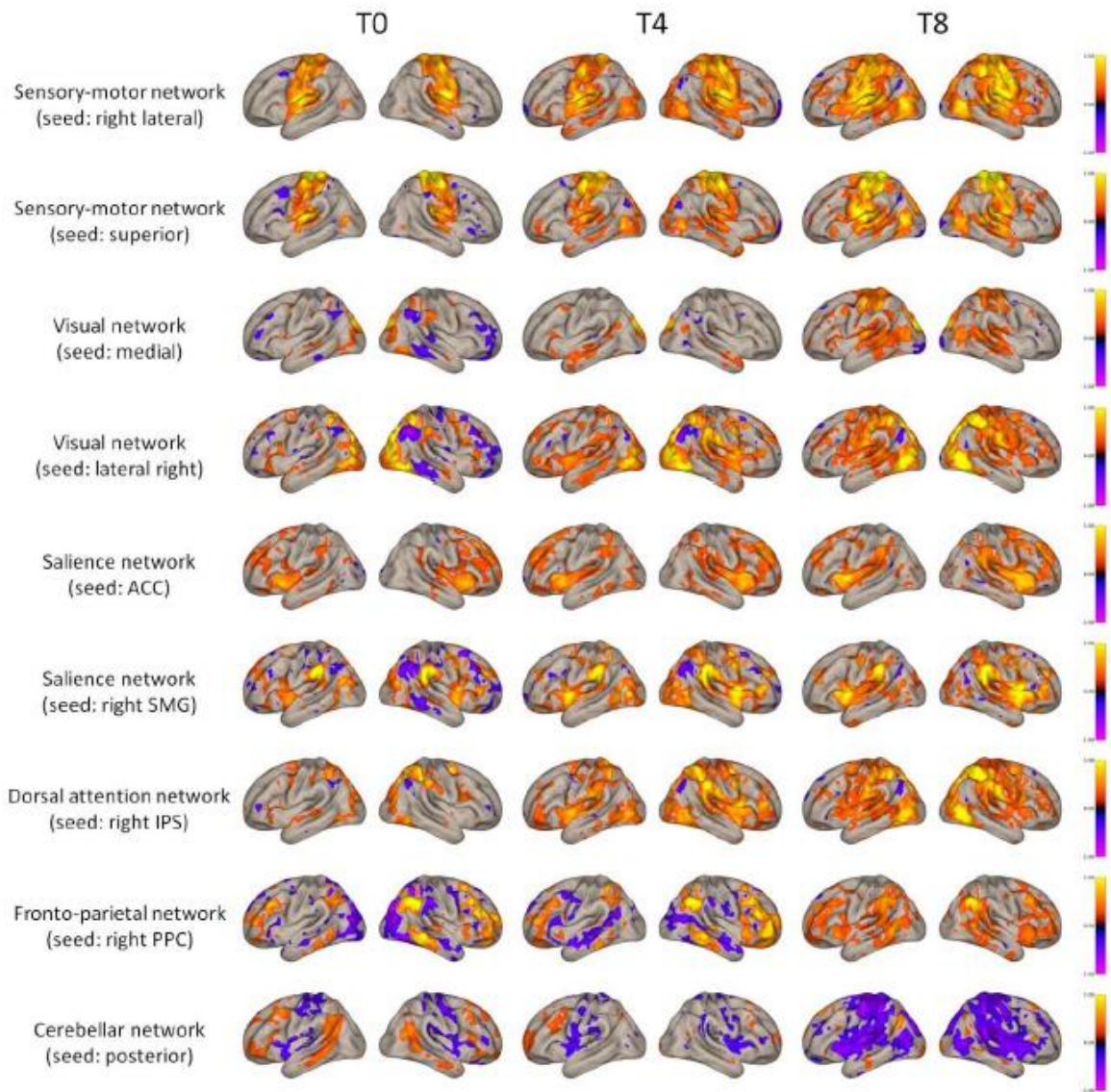


Figure 3. Resting-state fMRI results. Functional network connectivity identified by seed-based correlation (SBC) analyses of the resting-state fMRI data at T0 (before the intervention), T4 (immediately after the end of the 4-week intervention), and T8 (4 weeks after the end of the 4-week intervention) Richlan (2025).

2.4 Virtual Reality in Sport: Current Applications and Gaps

In recent years, driven by technological advancements, increased accessibility, and mobility of VR systems, there has been an enormous interest in VR applications across a broad range of recreational and high-performance domains, including sports (Bailenson, 2018; Greengard, 2019). In particular, adjusting environmental restrictions (i.e., altering the training circumstances) VR could be utilized to train in motor, cognitive, and mental abilities, strategy, and tactics (Cotterill, 2018; Schack et al., 2020). Across professional high-pressure, high-performance environments, VR provides interesting innovative solutions, especially regarding training and learning complex skills in otherwise costly or dangerous situations. When used properly – i.e., keeping session times short and taking breaks to avoid VR sickness (a.k.a. cybersickness, that is, symptoms resembling motion sickness) – VR allows safe and repeatable training tasks and affords complete control over the training environment including stimuli and difficulty (e.g., Wood et al., 2021). Therefore, it is considered a promising tool for skill acquisition and refinement in sports (Faure et al., 2019; Miles et al., 2012). Actually, about half of the English Premier League (football) clubs currently use VR technology to reduce the risk of head injuries during practice (Hart, 2018), target specific cognitive skills, and replicate matchday pressure (Cunningham, 2022). Additionally, by giving teams immersive experience of genuine training and games during injury breaks, something that would not be possible without virtual reality, VR gives the teams a promising tool for injury rehabilitation (Chen et al., 2009; Gokeler et al., 2014; Gumaa & Rehan Youssef, 2019). When it comes to physical demands, VR environments could be particularly safe and well-regulated for injured players during their rehabilitation. This is in contrast to training in the real world, and it can also offer intense mental training and potentially powerful cognitive stimulation. In addition, VR may be used for the evaluation of athlete injuries and movement patterns in a safe and well-controlled virtual environment (e.g., Buoite Stella et al., 2022; Deodato et al., 2023). Moreover, youth and academy players might benefit from VR, as simulations of loud fan chants or in-match pressure situations (e.g., opponents running toward them at a high pace) are designed to prepare them to deal with stressful situations in senior football at an early age. As recently shown, the presence or absence of spectators in a football stadium has substantial effects on the psychological states, behavior, and performance of football players and teams (Leitner & Richlan, 2021a, b; Leitner et al., 2022; Richlan et al., 2023). This may hold even more true for less experienced and younger players, who therefore might benefit even more from this kind of VR training. In addition to the

previously listed uses, virtual reality technology can be used to teach players to scan their environment visually, such as on a football field (Be Your Best, n.d.; Fortes et al., 2021; REZZIL | Rezzil - Cognitive Development and Analysis, n.d.). Since they scan the most at the professional level and a higher scanning frequency is associated with a higher chance of completing a pass, football players in central playing positions may find it particularly useful to improve their scanning behavior (Jordet et al., 2020). Athletes from a variety of sports could participate in learning, practice, and rehearsal through virtual reality training that would otherwise be physically taxing, risky, impractical, or costly (in terms of human, technological, or temporal resources) (Wood et al., 2021). Transferring abilities from VR to the real world should be feasible if the virtual sports environment elicits experiences and psychological states that are identical to or comparable to those of the real sports environment (Kim et al., 2019). Theoretically, athletes who excel in the real world should also perform well in the virtual world if training exercises in VR are an accurate and convincing portrayal of the abilities required in the real world (Gray, 2019). This idea of a performance-related differentiation between elite and non-elite athletes in VR is partially supported by evidence from an early study involving football (also known as soccer) goalkeepers whose task was to catch curved free kicks. The most experienced goalkeeper at the adult national level demonstrated the best performance in a challenging task in VR (Dessing & Craig, 2010). In this regard, VR training could be a particularly useful tool for skill acquisition if it is realistic enough to facilitate real-world transfer, or the conversion of possible training benefits in the virtual world into performance gains in the actual world. According to research on VR use, elite athletes perform better in VR when realistic representations of the key components of a talent are used, allowing VR to differentiate between the two groups (Gray, 2019; Harris et al., 2020). Accordingly, professional football players fared better on football workouts in virtual reality than academy and novice players, according to a study examining the validity of the VR program REZZIL® (Wood et al., 2021). Therefore, this VR program may offer significant advantages for safe football skill acquisition and improvement due to the chance to precisely practice skills that are linked to possible health issues in the actual world (e.g., headers). Richlan et al. (2023), conducting a review on the uses of VR in the context of sports performance, highlighted that the majority of published studies reported statistically significant training effects following interventions in VR compared with passive or active control conditions (e.g., using conventional training protocols). Thus, from a careful analysis of the research conducted on the relationship

between VR and sport performance, what clearly emerges are the promising results regarding the transferability of skills learned in virtual environments to real environments. However, given the intrinsic characteristics of this technology, the fundamental and widely demonstrated role played by executive functions in enhancing the performance of professional athletes, and the functionality of CMDT protocols, it seems to be necessary to broaden the landscape of scientific research by investigating how these factors can interact with each other in order to provide professional athletes with safe, coaching and innovative training tools and environments. In any case, this research aims to analyze the effects of some VR-based CMDT protocols particular to sports in order to determine whether there may be an additional application context for such technology. As a result of careful letter analysis, even though the clinical and athletic contexts showed significant benefits from the cognitive motor protocols, research on the effects of CMDT-VR protocols on improving executive function and athletic performance did not immediately surface. To this end, to inaugurate this line of research and considering the intrinsic demands of the various competitive contexts, two open-skills sporting activities were mainly selected. Indeed, in such environments, the elite athlete is one who is characterized by excellent spatial attention, divided attention, working memory and mentalizing capacity. He or she must be able to quickly adapt, change strategy and inhibit responses. Many of these abilities are referred to as game intelligence (Vestberg et al., 2012; 2017).

2.5 Football and Dance as Experimental Models for CMDT-VR Protocols

Considering the limited number of studies conducted on the relationship between CMDT and sport performance, the identification of the reference sample for experimental studies to be included in this thesis required careful and logical reasoning. Following a thorough analysis of the cognitive aspects that seem to discriminate well between closed-skills (CSE) and open-skills sports (OSE) activities, this last macro-category of reference was chosen. Indeed, from a simple environmental point of view, closed-skill sports are characterized by being practiced under stable and predictable conditions that remain largely constant or otherwise do not significantly influence the performance of the motor act. As a result, athletes engaged in such disciplines are not frequently required to adapt their execution to changing environmental variables. For these reasons, closed-skill sports are considered less cognitively demanding. In contrast, open-skill sports involve greater demands on executive skills, as they require continuous and flexible adaptations to dynamic and unpredictable contexts. Such characteristics could promote better performance in tasks that measure executive functions. For example, in soccer, if a player has planned a pass to a teammate but an opponent suddenly covers the passing line, the player will have to inhibit the previously planned motor gesture, thus activating behavioral inhibition processes (Heillman et al., 2022). Many studies show positive correlations between practicing open-skill sports and EF performance. (Jacobson et al., 2014) Studies that examined EFs in OSE report that OSE are superior to CSE in the context of development of EFs (Wang et al., 2013; Krenn et al., 2018; Kock et al., 2021). Therefore, in view of this evidence, we thought it more appropriate to identify two sporting modalities that can be defined as OSE on which to take advantage of the already proven benefits of CMDT (Lucia et al., 2021; 2023; 2024), adding VR technology to this practice. In this regard, football and dance were selected as sports activities with high cognitive demand. This assumption has found numerous confirmations in the literature. Indeed, a proficient and successful player must process substantial amounts of information rapidly while under mental pressure (Pruna & Bahdur, 2016). Numerous decisions need to be made swiftly and reevaluated dynamically based on the situational demands of the field. This requisite behavior involves specific cognitive anticipatory processes and creative decision-making where both precision and speed are optimized. Such cognitive and behavioral adeptness enables the soccer player to effectively "read the game" and form successful anticipatory expectations (Vestberg et al., 2017). In soccer, these mental skills are called "game intelligence" (Stratton et al., 2004). These skills mainly involve executive brain

functions (e.g., Goldstein & Naglieri, 2014; Barkley, 2012), but these functions are hardly trained in a specific manner in soccer players (Scharfen & Memmert, 2021). Moreover, enhanced perception, attention, sensorimotor integration and decision-making could permit optimal precision and speed to perform successfully. According to various authors, the athlete's capacity to provide a range of solutions that are appropriate and unique derives from efficient cognitive processing (e.g., Sternberg & Lubart 1999; Runco 2014; Memmert & Roca 2019). For instance, Vestberg, Gustavson, Maurex, Ingvar, and Petrovic (2012) found that high division soccer players performed better than lower division players on several cognitive function tests. Therefore, for successful performance, soccer players require not only technical and physical capabilities but also specific cognitive abilities (see Memmert, 2017a for a review). Decision-making is critical for successful performance, and it is well known that this cognitive skill is based on efficient perceptual and attentional capacities (e.g., Roca et al., 2021). Specifically, perception, sensorimotor integration and attention allow efficient environmental scanning to locate relevant cues while filtering out distractions. Research has shown that expert soccer players exhibit efficient visual search strategies, characterized by a considerable number of brief fixations directed at key areas of the field, such as unmarked teammates, open spaces, and opponents (Vaeyens et al., 2007a, b; Roca et al., 2013; Roca et al., 2018). These visual search strategies are linked to enhanced selective attention processes, helping athletes focus on task-specific knowledge structures essential for decision-making (Henderson, 2003; Cardoso et al., 2021). These perceptual-cognitive skills, cultivated through thousands of practices and reflection, support swift and accurate decisions under high-pressure situations during the competition (MacMahon & McPherson, 2009). Ultimately, technical proficiency, sensory-motor skills, and advanced cognitive functioning underpins the complex demands of soccer, reinforcing the notion that top performance hinges on the interplay between mind and body (Baker & Young, 2014; Memmert et al., 2010). The scientific literature on soccer presents many training methodologies that are both quantitatively and qualitatively diverse and often tailored to the needs of individual athletes. Although, multi-component training programs that include multiple kinds of exercises in the same training session (e.g., aerobic/anaerobic/muscular power, speed, strength, flexibility, and agility) are the most used (for reviews see Morgans et al., 2014; Thapa et al., 2021). However, while it is true that current research in the area of sport-specific motor training is abundant, the same cannot be said for the cognitive domain.

Similarly, what emerged from the literature that focused on the cognitive domains that seem to distinguish and characterize the professional dancer, dancers use complex movement patterns to translate visual and aural cues into motion. Dancers must closely observe one another in order to coordinate their movements as a group. Fine motor control, cognitive and motor anticipation, perception, attention, visuomotor imagination, time synchronization, and motor memory are only a few of the neurocognitive processes that must be executed concurrently when dancing (Bläsing et al., 2012; Golomer et al., 1999). A number of studies in the fields of motor control and cognitive sciences have examined the characteristics that appear to set dancers apart from athletes and non-dancers, given the notable influence of the cognitive and motor aspects on dancers' performance (Bruyneel, Mesure, Paré, & Bertrand, 2010; Chatfield, Krasnow, Herman, & Blessing, 2007). In particular, it appears that training in dancing enhances sensorimotor control systems that emphasize both static and dynamic balance. For example, compared to non-dancers, classically trained dancers have better postural control, can maintain particular postures for longer periods of time, and stride with more vertical alignment (Chatfield, Krasnow, Herman, & Blessing, 2007). Additionally, whether compared to non-dancers (Golomer, Cremieux, Dupui, Isableu, & Ohlmann, 1999; Golomer, Dupui, & Monod, 1997; Golomer, Dupui, & Monod 1997) or to less experienced dancers (Bruyneel, Mesure, Paré, & Bertrand, 2010), dancers exhibit higher balancing skills. Furthermore, these studies have looked into how dancers time their movements to the music and other dancers. Given that attentional distractions impair dancers' timing precision, attention seems to be a crucial element in preserving synchronization in dancing (Moncla et al., 2008a,b). Specifically, in the cognitive domain, professional dancers show increased activity in brain regions linked to memory and action recognition, according to neuroimaging studies (e.g., Burzynska et al., 2017; Wang et al., 2024). Studies using event-related potentials (ERP) and electroencephalography (EEG) looked at how professional dancers' brains processed visuospatial cognitive tasks. According to the results, which were compiled in the systematic review by Angelopoulou et al. (2022), professional dancers had higher synchrony of the theta, beta, and gamma bands (supporting communication between brain regions) and an earlier alpha band peak EEG frequency (associated with cognitive preparedness) than non-dancers. Given the circumstances, these studies suggested that dancers might have improved visuomotor cognitive abilities as a result of neuroplasticity brought on by consistent practice, which would make it easier for them to process their movements.

Thus, the choice of dance and football as sports activities for analyzing the benefits produced by CMDT-VR protocols has solid neuroscientific reasons. Dance, in particular, would represent a multimodal activity that integrates coordinated movement, rhythm and cognitive-emotional involvement, inducing structural and functional modifications of the nervous system, including increases in interhemispheric connectivity, plasticity in the hippocampus and improvements in mnemonic and attentional performance, even in old age. These neuroplastic changes make it an ideal model for modulating sensorimotor and spatial memory circuits, which are crucial in CMDT protocols. Furthermore, the possibility of freely manipulating such protocols through VR suggests innumerable benefits in enhancing the sense-perceptual aspect that seems to distinguish the dancer from other athletes. Similarly, football appears to require fine sensorimotor adaptation and rapid decision-making in dynamic, changing and highly complex contexts. Not surprisingly, it would intensively stimulate executive functions such as inhibition, working memory and cognitive flexibility in highly variable scenarios, as demonstrated by the scientific evidence proposed in this thesis work. Such data underlines the opportunity to develop CMDT-VR based on ecologically valid and sport-specific tasks, where VR immersiveness could amplify learning through realistic sensory and contextual feedback, reinforcing neuroplastic mechanisms. Finally, immersive simulation allows critical variables - e.g., pace, tactical complexity, presence or absence of opponent stimuli - to be manipulated in a controlled and reproducible manner. This could facilitate cause-effect analysis between stimuli, neural activation and motor performance, laying the foundation for potential transitions towards application in real-world competitive environments.

Chapter 3: Electrophysiology of action and cognition

3.1 Relevant event-related potential (ERP) markers in cognitive and action neuroscience

EEG measures the electrical activity of large, synchronously firing populations of neurons in the brain with electrodes placed on the scalp. One of the most significant applications of EEG is the analysis of event-related potentials (ERPs), which are brain responses that are time-locked to specific sensory, cognitive, or motor events (e.g., Di Russo et al., 2019). ERPs are very small voltages generated in the brain structures in response to specific events or stimuli (e.g., Blackwood & Muir, 1990). EEG alterations that are time-locked to motor, sensory, or cognitive events offer a secure and non-invasive method for researching the psychophysiological correlates of mental processes. Many different types of sensory, cognitive, or motor events can trigger event-related potential. They are believed to represent the total activity of postsynaptic potentials generated when dozens or millions of cortical pyramidal neurons with comparable orientations fire simultaneously during information processing (e.g., Peterson et al. 1995). Each ERP component reflects a different stage of cognitive or motor processing, and these components are typically labeled based on their polarity (positive or negative) and timing (in milliseconds) from stimulus onset. Depending on whether the component precedes or follows the stimulus (triggering event) onset, preparatory (anticipatory) and reactive components can be described, respectively. Slow-potential pre-stimulus ERP components can start up to a few seconds before sensory or motor events. Taken together, the pre-stimulus components make it possible to observe the early and proactive phases of action preparation and cognitive anticipation. These markers are crucial for understanding how the brain selectively prepares perceptual and motor processes according to context and goal and constitute a central axis in understanding sports expertise and neurocognitive optimization strategies. The primary pre-stimulus elements include:

The Bereitschaftspotential (BP), also known as the readiness potential (RP). According to Berchicci et al. (2019), this signal is associated with motor preparation, signifying the slow activation of premotor brain areas and the behavioral readiness for upcoming motions. It is a slow-

rising potential detected in the frontal–central areas of the scalp around 1500-1000 msec before the initiation of voluntary motor acts (e.g., Shibasaki & Hallett, 2006). Recent studies have suggested that its magnitude may be modulated by the complexity of the movement, the degree of uncertainty associated with the task, and the individual's motor skills (e.g., Casella et al., 2024; Berchicci et al., 2014). The prefrontal negativity (pN) is linked to cognitive preparation for the upcoming stimuli and rises from the prefrontal cortex (PFC) (e.g., Bianco et al. 2017). pN originates in the inferior frontal gyrus (e.g., Di Russo et al., 2016; Casella et al., 2024), 1000 ms before the stimulus onset and serves as the neural correlate of proactive cognitive control (mainly inhibitory), acting as a "braking" mechanism in the brain (e.g., Bianco et al., 2017). The visual negativity (VN) is pre-stimulus excitability initiating almost one second before the stimulus onset and rising from bilateral extrastriate visual areas (e.g., Di Russo et al., 2019; Di Russo et al., 2021). Specifically, it would represent sensory anticipation of visual processing and is typically recorded on occipital regions. This component reflects the perceptual preparation and anticipated orientation of visual attention, especially in tasks in which discrimination of the visual stimulus is essential for the motor response. The vN is considered an electrophysiological marker of the interaction between primary visual areas and spatial attention systems (Di Russo et al., 2019; Bianco et al., 2020).

Post-stimulus ERP components are evoked by stimuli or events and vary according to the stimulus modality. The P1 is a positive component typically observed in the 80-130 ms range after stimulus onset, which the early part of its wave arises from generators in the dorsal extrastriate occipital cortex and the later part of the P1 from sources in the ventral extrastriate cortex (e.g., Di Russo et al., 2002). Studies show that the P1 amplitude increases when attention is directed to a specific spatial location. This suggests its involvement in top-down attentional processes. The P1 reflects exogenous processes modulated by the physical characteristics of the stimulus (i.e., brightness or color for visual stimuli) (e.g., Coles & Rugg, 1995). The N1 in the visual domain rises around 100–200 ms after a visual stimulus. It reflects early stages of visual feature extractions, such as edge detection, motion, or color, and arises primarily from the extrastriate visual cortex (occipital and parietal regions), with contributions from frontal areas (e.g., Brem et al., 2018). The pN1 arises typically from the prefrontal cortex, around 110–160 ms after stimulus onset, and is modulated by factors such as attention, task complexity, congruence, and stimulus novelty. The pN1 could reflect the focusing of attention at the first level of perceptual processing (e.g., Perri et al., 2017). The

Pp1 is a positive polarity ERP waveform following an early sensory or cognitive event, possibly around 100–200 ms post-stimulus. The prefrontal P2 occurs between 200–400 ms post-stimulus onset from the prefrontal cortex and has been linked to response-related processing of sensory evidence accumulation and stimulus categorization when decision-making is required, such as in discrimination response tasks (e.g., Berchicci et al., 2016; Di Russo et al., 2016). Furthermore, the pP2 is often modulated by the difficulty of a task or the degree of congruency between sensory inputs and motor actions since it's linked to the sensory evaluation process. Comparing the target with the non-target with the differential pP2 peaking at 300 ms better shows the described processes. The P3 involves a broader network, including parietal, frontal, and motor-related areas, reflecting its role in both sensory processing and motor preparation. It is one of the most studied ERP components and typically occurs between 300 and 600 milliseconds post-stimulus. It is linked to attention and cognitive processes such as decision-making and memory updating. The P3 is divided into two main subcomponents: the P3a, related to attentional shifts and novelty detection; and the P3b, associated with context updating and working memory. The P3 is often most prominent over parietal electrode sites rising about 250–500 ms post-stimulus onset. It is a critical marker of cognitive processing, reflecting attention, stimulus evaluation, and working memory updates (e.g., Borra et al., 2021).

3.2 ERP Correlates of Sport Excellence

Research in cognitive and action neuroscience has revealed that a large amount of brain circuitry is involved in comprehending, anticipating, and responding to the actions of others, going beyond the study of fundamental cognitive processes like perception, memory, and attention (Frith & Frith, 2010). In recent years, the investigation of anticipatory neural processing, using ERPs, has made an essential contribution to the understanding of the proactive cognitive processes underlying sporting excellence. A large portion of the research focuses on the P3 component, which is an indicator of attentional resources allocated to stimulus processing and categorization and occurs 300–400 ms following stimulus onset (e.g., Polich, 2007). Radlo, Janelle, Barba, and Frelich (2001) conducted a study in which participants were presented with videos depicting a baseball pitcher intent on throwing fastballs and curveballs, while electroencephalographic (EEG) activity was recorded. The subjects' task was to press a button as quickly as possible to indicate the type

of pitch observed. The results showed that the experienced players were more accurate overall than the intermediate-level subjects, responded faster in the presence of curveballs, and were less influenced by anticipatory verbal cues. The most interesting result from the study was a significant interaction between the type of pitch (fastball vs. curveball) and the amplitude of the P3 component. In the presence of curveballs, intermediate hitters exhibited significantly higher P3 amplitudes, while experienced hitters had similar amplitudes for both fastballs and curveballs. Fastballs, considered the default pitch, fast but straight, were associated with shorter P3 latencies. In contrast, curveballs, more difficult to throw accurately and characterized by a more curved trajectory, were also more complex to hit. The increase in P3 amplitude in intermediate hitters when viewing curveballs could reflect a greater difficulty in processing such pitches. In contrast, in experienced hitters, the constant amplitude between the two pitch types suggests a lower expectation for fastballs and greater familiarity in discriminating between the two types, indicating greater efficiency and automation in processing. These results support the “neural efficiency” hypothesis that experienced athletes activate fewer cognitive resources to achieve superior performance. In a follow-up study conducted on cricket players, Taliep et al. (2008) analyzed the P3 component while watching video clips in which the bowlers performed inswing or outswing. The results showed shorter P3 latencies and a tendency towards smaller amplitudes in experienced players than in less experienced players, interpreted as a sign of greater automation in cognitive processes typical of high-level athletes. However, not all data fully support the neural efficiency hypothesis. For example, Feng, Zhou, Zhang and Tian (2010) observed that elite fencers were more accurate than general-level athletes in predicting their opponent's response during a partially obscured fencing attack, but this performance superiority was associated with an increased amplitude of the P1, P3 components and slow positive potentials, contrary to the idea that experience results in reduced neural activation. Similarly, Jin et al. (2011) found that expert badminton players, while being more accurate in predicting the trajectory of hits than controls, showed greater amplitudes of parietal P3, parietal-occipital P2 and slow positive potentials. Furthermore, in a previous study, Jin et al. (2010) showed an amplification of the C1 component, an occipital wave associated with early visual processing, in the same athletes. These results suggest that, in some sporting contexts, expertise may involve a greater involvement of neural resources, perhaps linked to the complexity and specificity of the anticipatory task. These apparent discrepancies in the results seem to stem from differences in the time point chosen as the reference

for the average ERP analysis. In previous studies, the reference event was either the moment when the pitcher raised the ball to ear height before the pitch (Radlo et al., 2001) or the instant when the ball left the pitcher's hand (Taliep et al., 2008). In both cases, these were events without marked visual transitions, and therefore no visual evoked potential (VEP) was generated at the moment the ball was released or lifted. In the data presented by Taliep et al. (2008), for example, no obvious P1 or N1 components emerge in the averages of the ERP traces, but a prominent P300 is observed, indicative of attentional and decision-making processes. Such decision-making processes are based on information available prior to the reference event, such as the kinematics of the opponent's body. In later studies, however, the reference event was the onset of the video, which occurred 400-480 ms before the end of the fencing attack (Feng et al., 2010), or the contact between racket and shuttlecock in badminton (Jin et al., 2011). In these cases, the presence of an overt visual stimulus resulted in the emergence of robust VEPs, which preceded the neural response related to the predictive processing of kinematic signals. In agreement with this explanation, Jin et al. (2011) concluded that the effects of expertise observed in their ERP data reflected an increased focus on situational cues or motivational differences, as they occurred at too early a stage to be attributed to the motor resonance effects typically found in temporal occlusion studies. Consequently, the effects of expertise on the P300 component appear to depend closely on the temporal moment chosen as a reference with respect to the stimulus events and proposed tasks. Liu et al. (2017) conducted a pre-post training EEG/ERP study aimed at investigating anticipatory processes. Novice students underwent a pre-test in which they had to predict the shuttlecock landing position from temporarily occluded videos of badminton hits while recording EEG activity. Subsequently, the experimental group participated in a 12-week training program, while the control group received no training. At the end of the period, both groups underwent a post-test with EEG recording. The trained group showed a significant improvement in accuracy and speed of response. Furthermore, the amplitude of the parietal P3 component, measured in relation to the start of the video, increased in the trained group and decreased in the untrained group. Another relevant neurophysiological effect was the increase in frontal N2 - an index of cognitive control - in the experimental group, interpreted as an expression of an enhancement of inhibitory mechanisms that facilitate more effective attentional selection, contributing to the performance improvement in the prediction task. A similar increase in the N2 component was already found by Nakamoto and Mori (2012) in a study of experienced baseball players engaged in a simulation task

in which the ball could decelerate suddenly during trajectory. Experienced players proved more accurate in predicting the moment of impact, suggesting a more effective inhibition of the initially incorrect motor program. Wang and Tu (2017) used Posner's (1980) cueing task to investigate badminton players' processing of their opponent's kinematic signals. The task involved the appearance of a shuttlecock-shaped icon, to the left or right of a fixation point, to which participants had to respond by pressing a button. The cue consisted of a 200 ms image depicting a badminton player in one of four possible configurations: low blow to the left, low blow to the right, preparation movement (backswing) to the left, or to the right. The most significant result that emerged concerns contingent negative variance (CNV), an ERP component that reflects the anticipation of an impending stimulus. Experts showed a lower CNV amplitude than novices, following the vision of a more skillfully executed movement. This finding was interpreted as indicative of greater automaticity in backswing processing by expert athletes, consistent with the “neural efficiency” hypothesis. Wang and colleagues (2020) investigated the neural correlates of cognitive ability in elite soccer players by analyzing EEG activity during the performance of a Go/No-Go task. The results showed that, compared with a control group, soccer players showed significantly faster reaction times and greater accuracy in discriminating target stimuli, confirming greater efficiency in decision making. At the neurophysiological level, elite athletes showed greater amplitude of the N2 component and shorter latency of the P3 component, both of which are associated with response conflict and decision making, respectively. These data suggest that elite soccer players possess a superior capacity for response inhibition and more rapid stimulus evaluation, reflecting greater efficiency of the attentional and executive control systems. The study thus provides further support for the “neural efficiency” hypothesis, according to which sports expertise is associated with a functional reorganization of the cognitive system, manifested in faster and more efficient processing of performance-relevant information. Moreover, Veliks and colleagues (2024) examined differences in neural activation patterns and behavioral performance between open-skill (basketball players) and closed-skill (track and field runners) athletes during a Choice Response Time task with simultaneous EEG recording. Although no significant differences in mean reaction times emerged between the groups, open-skill athletes showed less asymmetry between dominant and non-dominant hands, indicating a more symmetrical and efficient motor control. At the neurophysiological level, ERP analyses revealed more intense and earlier frontal activity (F3-F4 electrodes) in open-skill athletes, with greater activity in the right frontal cortex

(F4) around 200 ms, suggesting a more pronounced involvement in inhibitory control and perceptual processing. In contrast, the central motor regions (C3-C4) showed more symmetrical patterns and less pre-response activation in basketball players than in runners, suggesting more efficient motor regulation. These results indicate that the practice of sport in highly dynamic and unpredictable contexts, such as basketball, may promote greater integration between executive control and motor response, reinforcing the hypothesis of a neurofunctional specialization dependent on the type of sport practiced. Overall, neuroscientific evidence gathered through the analysis of ERP components in sports contexts suggests that athletic expertise is the result of refined optimization of anticipatory and decision-making processes. Data from different disciplines—such as baseball, cricket, fencing, badminton, and soccer—show that elite athletes not only respond faster and more accurately to relevant stimuli, but also manifest a different configuration of neurophysiological patterns, evidenced by specific modulation of components such as P3, N2, CNV, P1, and C1. In particular, the lower latencies and higher or lower amplitudes of these components—depending on the type of task and stage of processing (anticipatory or reactive)—reflect greater efficiency in encoding, selecting and inhibiting action-relevant information, supporting the theory of “neural efficiency.”

However, the heterogeneity of the results, with some evidence reporting increased neural activity in experts compared to novices, and others showing the opposite, suggests that sport expertise enhances neural flexibility and allows better adaptation of cognitive control to the requested task. (e.g., Sanchez-Lopez et al, 2014). Athletes are able to effective functional allocation of brain resources in relation to task complexity and temporal phase of processing. Ultimately, the ERP approach allows the neurocognitive dynamics underlying elite sports performance to be captured with extraordinary temporal precision, offering privileged access to the analysis of proactive control, inhibition, and decision evaluation mechanisms. This information, in addition to enriching theoretical understanding of sport skills, represents a potential application tool for the design of targeted interventions—such as neurocognitive training programs—aimed at enhancing anticipatory and decision-making efficacy in athletes, particularly in the high variability and time pressure contexts typical of open-skill sports.

Chapter 4: Empirical studies

4.1 Study 1: Effects of a virtual reality reaction training protocol on physical and cognitive skills of young adults and their neural correlates: A randomized controlled-trial study.

Abstract: Increasing evidence shows that virtual reality (VR) training is highly effective in cognitive and motor rehabilitation. Another modern form of training is the cognitive-motor dual-task training (CMDT) which has been demonstrated to rapidly improve physical and cognitive functions in real environments. This study aims to test whether a VR-based CMDT protocol can be used for motor and cognitive skill enhancement in young healthy subjects. For this aim, 24 university students participated in a randomized-control trial. The experimental group participated in a 5-week virtual reality reaction training (VRRT), performing 30-minute sessions once a week. The control group did not receive any training but was tested twice with the same measures and temporal distance as the experimental group. Before and after the intervention, motor, cognitive, and electrophysiological measures were assessed. Results showed that following the VRRT the response time for both physical and cognitive tests was improved by about 14% and 12%, respectively, while the control group did not show significant changes. Moreover, electrophysiological data revealed a significant increase in anticipatory motor readiness in premotor brain areas in the experimental group only, but also cognitive top-down control tended to be increased in prefrontal areas after the VRRT. This training protocol in VR modality seems as effective as other CMDT training methodologies done in real modality. Still, it has the advance to be more flexible and more user-friendly compared to standard training. The VRRT's efficacy on physical and cognitive functions indicates that virtual reality applications can be used by the young population not only for entertainment purposes but also as cognitive-motor training.

Keywords: virtual reality; physical performance; cognitive performance; cognitive-motor training; event-related potential; task preparation

Introduction

Virtual reality (VR) is defined as the “interactive visualization of virtual images enhanced by special processing and nonvisual display modes: to convince participants that they are immersed in a synthetic space” (Ellis, 1994). VR technology has advanced significantly in recent years and seems to be among the most intriguing and promising developments in computer graphics. Specifically, it uses interactive devices to artificially generate an environment as close to the real world as possible, in which users can interact with its tridimensional entities (Gatica Rojas et al., 2014; Tan et al., 2019; Tan et al., 2019). One of the greatest values of VR is that it can be used as a training methodology to increase cognitive and motor performance through highly immersive scenarios (González-Fernández & Feldman, 2021). VR-based training presents undeniable advantages compared to real training for many reasons: Any details of the environment can be fully manipulated, always keeping it safe and controlled (Tierl et al., 2018). The physical and cognitive load can be finely graduated to be suited to the individual and increased or decreased according to the training goals (Tierl et al., 2018; Rizzo et al., 2004). VR training allows multimodal and immediate feedback on performance that facilitates learning (Rizzo et al., 2004) and helps the trainer in modulating the task. In addition, immediate response-related feedback may reduce uncertainty and anxiety about performance (Mussini & Di Russo, 2023). Finally, VR training can be executed at home with remote supervision. In recent years, the scientific literature has focused on VR training through a combination of technologies, since it seems to offer an excellent improvement in specific health needs, including cognitive enhancement and rehabilitation; particularly in the area of cognitive impairment (García-Betances et al., 2015). Not surprisingly, several studies have confirmed that specific VR training can induce states of relaxation and positively stimulate cognitive and executive functioning. These benefits would be provided by the ability to immerse users in 360 degrees within the desired scenario. These scenarios, unlike real life, may consist of many stimuli and distractors with which the user must interface to achieve one or more specific goals (Park et al., 2020). Hence, among the main purposes of VR training, the facilitation of cognitive modeling and enhancement through virtual environments specifically designed to simulate both the external and internal worlds assumes centrality. Previous studies have suggested that cognitive training in VR may improve not only people's cognitive functions and emotional experiences (García-Betances et al., 2015; Riva et al., 2019; Park et al., 2020) but also their daily living skills (Kim et al., 2019; Liao et al., 2020). Thus,

VR cognitive training can stimulate the brain to improve its cognitive functions. Among the main positive effects on relevant neurobiological mechanisms, cognitive plasticity, and neuroplasticity are the most relevant (Belleville et al., 2011; Szelenberger et al., 2020; Vlachos & Scarmeas, 2019). Considering these findings, it seems clear that, currently, VR is considered a supportive tool for the treatment of some neuropsychological, and psychological disorders (i.e., anxiety, depression, and cognitive decline) and in specific cases, for post-stroke rehabilitation (Vlachos & Scarmeas, 2019). Another modern form of valuable training is the cognitive-motor dual-task training (CMDT) which simultaneously combines physical and cognitive exercises. Many studies on CMDT demonstrated its effectiveness in rapidly improving both physical and cognitive functions in both old (Lucia et al., 2024) and young people (Lucia et al., 2021). Studies investigating the neural bases of the CMDT effects indicated that may stimulate anticipatory brain function in prefrontal and premotor areas allowing more predictive neural resources deployed on action anticipation in sensorimotor cognitive tasks (Lucia et al., 2024; Lucia et al., 2021). The studies on old people used the CMDT to counteract age-related cognitive and motor decline. The studies on young people regarded high-level athletes and the CMDT was used to improve the sport performance. However, while the aforementioned areas of VR application are commendable and worthy of special attention, there seems to be a significant gap in the literature about the physical and cognitive benefits that can be experienced from specific VR training in the healthy population. Commercial VR systems are mainly used by young adults for entertainment, but this technology may potentially offer numerous benefits in different areas of daily life such as increased performance in school, work, and sports (Rojas-Sánchez et al., 2023; Sattar et al., 2020). This paper aimed to test a VR training protocol on healthy people, not only to expand our knowledge in VR research but also to verify whether the numerous benefits offered by VR training in patients could be useful to the healthy population too. To maximize the benefit offered by VR on cognitive and motor performance, we used the CMDT as a training modality to be used in VR. Specifically, we expect that (such as for the CMDT in the real environment), VR-based CMDT training could also improve physical and cognitive performance in young healthy people. To do this, we used a device and software currently available in stores. If effective, such training could offer numerous benefits in different areas of daily life, increasing performance in school, work, and sports. Indeed, in these areas, cognitive functions play a crucial role in achieving successful outcomes (Otero et al., n.d.; Erickson et al., 2019). We also aimed to test if VR-based CMDT training could affect

anticipatory brain processing. Specifically, given the results obtained by Lucia et al. (Lucia et al., 2024; Lucia et al., 2021), the main objective of this research project was to investigate the influence of VRRT on specific ERP components. Specifically, we hypothesized that, following the training performed, the experimental group would report significant benefits in the components prefrontal negativity (pN) and Bereitschaftspotential (BP); which reflect cognitive anticipation and motor preparation, respectively. Similarly, given the characteristics of VRRT, we hypothesized that the experimental group would report significant benefits in motor testing compared with the control group. To do this, we use techniques from neurophysiology to study the quick and intricate neural processing that takes place when performing motor and cognitive activities. More precisely, event-related potentials (ERPs) and electroencephalography (EEG) allow for the millisecond-accuracy detection of brain processes. Because of their excellent temporal precision, ERPs have been used to successfully detect the temporal course of cognitive processes spanning from task preparation to motor execution (Di Russo et al., 2019). According to ERP research, certain training regimens might affect the anticipatory brain activity that is necessary for completing difficult sensory-motor cognitive tasks (Lucia et al., 2024; Lucia et al., 2021). Response discrimination tasks (DRT) like the Go/No-go paradigm have been used in these investigations because they strongly engage anticipatory cognitive functions (Di Russo et al., 2019; Di Russo et al., 2016). In fact, their attention was drawn to pre-stimulus anticipatory ERP elements, such as prefrontal negativity (pN) and Bereitschaftspotential (BP), which begin to manifest around one second before the beginning of the stimulus. It has been demonstrated that in DRTs, response accuracy is predicted by pN, meaning that the higher the pN, the lower the error rate, and response time (RT) is predicted by BP amplitude, meaning that the greater the BP, the quicker the RT. While the pN, which originates from the inferior frontal gyrus (Di Russo et al., 2016), has been linked to response accuracy, proactive cognitive functions like top-down attention and inhibition in the prefrontal cortex for complex tasks (Di Russo et al., 2019; Di Russo et al., 2016), the BP is an anticipatory readiness potential that reflects the excitability of the supplementary motor and cingulate areas and emerges before any voluntary act (Shibasaki & Hallett, 2006). Additionally, it has been suggested that these elements provide the neurological foundation of an activation/inhibition (braking/accelerating) cognitive system. A system that influences the speed/accuracy tradeoff by foreseeing and predicting future actions and occurrences (Di Russo et al., 2019). Furthermore, results from CMDT interventions that explored the effect on behavioral performance (RT, accuracy) and investigated

the effect of plasticity and compensation on BP and pN in basketball players already provide evidence of the effectiveness of these training protocols (Lucia et al., 2024; Lucia et al., 2021). According to this literature, we expect that in case of improvement in response time and accuracy, increased BP and pN amplitudes should be correspondingly found.

Materials and Methods

Participants

Using Cohen's f statistics to estimate effect size, the G*power 3.1.9.2 software was used to determine the sample size. Based on a work with a comparable design and measures (Lucia et al., 2024), we set the predicted effect size $f(V)$ for the current mixed 2X2 ANOVA design at 0.31. The α level was set at 0.05, and the intended power $(1-\beta)$ at 0.95 (estimated sample size=24). Thus, for the study, a total of twenty-four university students—twelve males and twelve females—with a mean age of 24.5 years ($SD=2.5$) were enlisted. The following conditions had to be met in order for a participant to be considered for inclusion: normal or corrected-to-normal eyesight; no medical illness, no neurological or psychiatric illnesses; and no medication during the trial session. Before taking part in the study, the participants provided their informed consent in line with the Declaration of Helsinki, with clearance from the University of Rome's "Foro Italico" local ethics council.

Procedure

In these randomized-control trials, participants were pseudo-randomly assigned to two groups of 12: the experimental (Exp) and the control (Con) group balancing them for the daily level of physical activity, measured using the International Physical Activity Questionnaire (IPAQ) (Lee et al., 2011). Preliminary t-test indicated that groups did not differ for age, education, and socioeconomic status ($t(23)>1$). Both groups participated in two screening test sessions at six weeks of distance including physical, cognitive, and electrophysiological measures. During this period, the Exp group performed five 30-minute sessions of VRRT, described below, once a week. The control group was screened twice only to control the learning effect of the employed measures.

Screening

Physical test

To measure physical performance, the 10-meter sprint test was used. For this test, a Witty-SEM device (Microgate, Bolzano, Italy) was placed in front of the standing participant at 1.5 m height. The display showed a 3-2-1 countdown (number duration 1 s), became black for a random interval from 1 to 5 s, and then turned to green indicating the participant to start a 10-meter linear sprint as fast as possible. A photocell, connected to the Witty-SEM device and located at the beginning of the 10-m running track, measured the sprint reaction time. Each participant performed three attempts, but only the best reaction time was recorded.

Cognitive test

A visuomotor discrimination response task (DRT), commonly referred to as "Go/No-go," was conducted as part of the EEG recording process. Participants had the EEG cap fitted over their scalps, and then they were tested in a soundproof, dimly lighted room. Participants sat in front of a computer screen that was 114 centimeters away from their eyes, and they touched a response box with their right index finger. A fixation point appeared at the center of the screen on a black background at the beginning of each trial and stayed there the entire time. As shown in Figure 1, four visual stimuli, each with an equal probability ($p=0.25$) and represented by square configurations measuring $4 \times 4^\circ$ made up of vertical and/or horizontal bars, were shown at random for 250 ms each. To avoid anticipation and ERP overlaps with either the previous or upcoming stimulus, the intervals between stimulus onsets were spaced out by one to two seconds. Two predetermined target stimuli were shown to the participants ($p=0.5$), and they were told to hit the button as soon as they appeared. Non-target stimuli were not to be responded to ($p=0.5$). The instructions placed equal emphasis on precision and quickness. The presentation order of the stimuli was not predetermined. There were gaps of two minutes between each run. Ten runs were carried out in all, resulting in roughly 400 trials for every stimulus category in a 25–30 minute period.

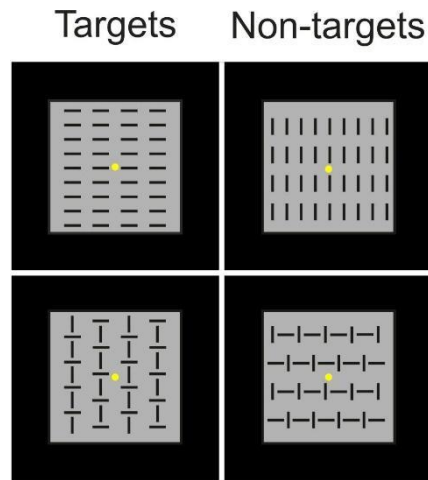


Figure 1. Depiction of the stimuli employed in the cognitive task, distinguishing between target and non-target stimuli.

Behavioral data

The average of response time (RT) for accurate trials was computed. Accuracy was determined by combining the percentage of commission errors (i.e., responses to non-target stimuli) and omission errors (i.e., missed responses to target stimuli).

EEG recording and analysis

EEG recordings were made using the BrainVision Recorder 1.2 software receiving signals from three BrainAmp™ amplifiers. Two of them were connected to 64 active scalp electrodes (ActiCap™) and the Analyzer 2.3 software was used for data processing (all by BrainProducts GmbH., Gilching, Germany). The channels were positioned at the following sites: Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz, Pz, Oz, FC1, FC2, FC5, FC6, CP1, CP2, CP5, CP6, PO3, PO4, AF3, AF4, F1, F2, F5, F6, FC3, FC4, C1, C2, C5, C6, CP3, CP4, P1, P2, PO7, PO8, FT7, FT8, TP7, TP8, F9, F10, FT9, FT10, T9, T10, P9, P10, Iz, AF7, AF8, CPz. The scalp electrodes were mounted according to the 10-10 International System and the position is showed in figure 5. The M1-M2 electrodes was set as reference. A Butterworth zero-phase filter (0.01–60 Hz; second order) was used to band-pass filter the amplified EEG signals, which were then stored for offline analysis. The data were digitized at 250 Hz. The third BrainAmp amplifier (ExG type) was used to record the electrooculogram (EOG), which tracked eye movements in

bipolar mode. Electrodes were positioned above the outer canthi of the left and right eyes to record the horizontal EOG, while electrodes were put below and above the left eye to capture the vertical EOG. Impedances of the electrodes were kept below 5 K Ω . Analysis of the blink and vertical eye movement artifacts was done automatically with Analyzer 2.3's independent component analysis too using the "Meaned Slope" algorithm". Subsequently, to remove other artifacts due to sweating, muscle tension, and/or heartbeats, periods where amplitudes exceeded the threshold of $\pm 70 \mu\text{V}$ were excluded from further analysis. EEG data was segmented into 1300 ms epochs, commencing 1100 ms prior to stimulus onset and concluding 200 ms following stimulus onset, in order to assess pre-stimulus activity. A baseline of -1100/-900 ms was applied to the first 200 ms. Target and non-target trials were averaged since the stimulus category was unpredictable before stimulus onset. To establish intervals and electrodes to be used for statistical analysis, the "collapsed localizer" approach was used. The collapsed localizer is the average of all considered ERP data across all groups and conditions, as described in Luck et al. (2017). This approach ensures that the intervals and electrodes selected for analysis are representative and unbiased across different experimental conditions. To choose the analysis interval, the global field power (GFP), which represents ERP spatial variability across all scalp electrodes simultaneously, was computed (Skrandies et al., 1990). For additional analysis, this meant determining the pre-stimulus interval during which the GFP surpassed 70% of its highest value. The GFP-based method identified a range of -300 ms to 0 ms, within which the mean amplitude under all conditions was calculated for statistical analysis. In the interval set by the collapsed localizer, electrodes exhibiting amplitudes greater than 70% of the maximum value were averaged into spatial pools and used for statistical analysis. The medial prefrontal activity of the pN and the medial centro-parietal activity of the BP components were the two main activity foci that were identified. The pre-frontal pool, which included the electrodes Fpz, Fp2, AFz, and AF4 to represent the pN, and the centroparietal pool, which included the electrodes CP2, CPz, C2, and Pz to represent the BP.

Intervention

The Exp group performed five 30-minute sessions (once a week) of VR training using a Meta Quest 2 system (Meta Platforms, Inc) and the "Rezzil Player" software, available in Meta Quest store. This software was chosen because included a collection of specific sports training and some of them fulfilled the CMDT requirements since included simultaneous motor and cognitive

exercises with incremental cognitive and motor loads [20-22]. The training used was the “reaction wall” that requires participants to touch, as quickly as possible, the stimuli that light up in a grid of lights wall in front of him/her. Red and blue stimuli had to be touched with the right and left hand, respectively, and the stimulus position randomly varied. The training has incremental levels of difficulty; at the first level, the stimulus duration (500 ms) and interstimulus interval (1000 ms) were fixed. At the second level, these durations decreased proportionally to the speed of the subject's response. Each level had four different difficulties grades, in terms of the stimuli present in the visual field: a) a 3x3 grid subtending 30° of horizontal visual angle with nine stimulus positions; b) a 5x4 grid subtending 60° with 20 positions; c) a 10x4 grid subtending 180° with 40 positions; d) 20x4 grid subtending 360° with 40 positions. In the first level, each grid lasted 60 seconds with 30 seconds of break in between. In the second level, grids lasted 120 seconds with 30-second breaks. The four grids visualized by participants are shown in Figure 2.

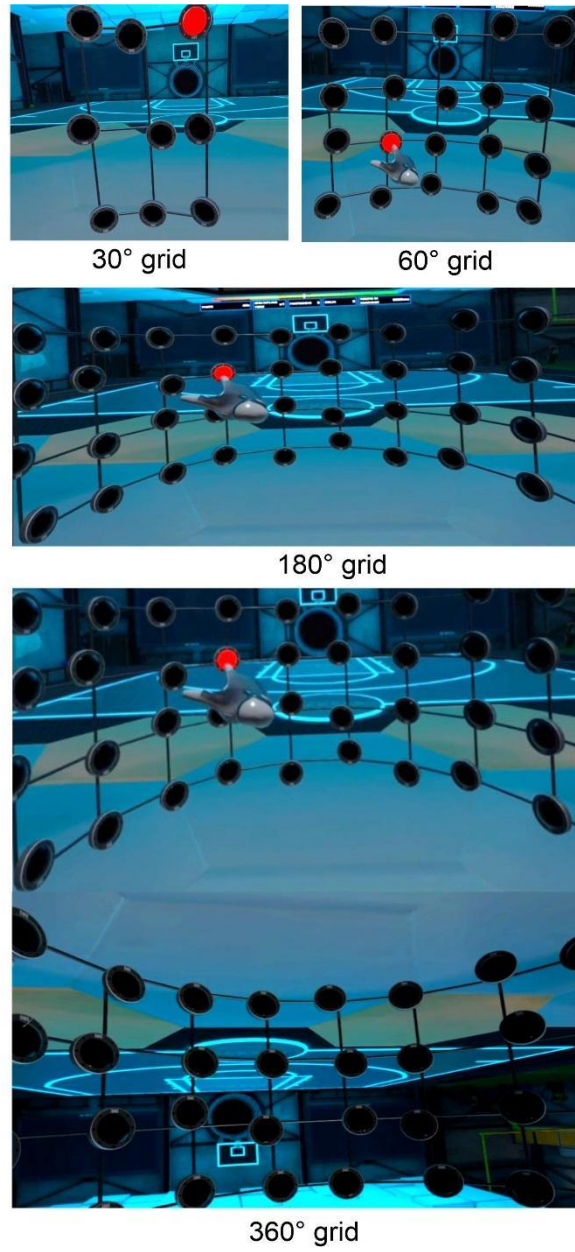


Figure 2. Views of the VR training at the four grades of difficulty. The red circle represents the target stimulus.

Statistical Analysis

The Shapiro-Wilk's *W* test was used to evaluate the assumption of normality for each measure. The results showed that all of the measures were non-significant, indicating that they adhered to normal distributions. Using Levene's test for equality of variance to assess the homoscedasticity assumption, no sample homoscedasticity violation was found. All measurements were subjected to mixed 2X2 ANOVAs with Group (Exp vs. Con) and Time (Pre-test vs. Post-test) as the factors after these preliminary tests. The reported effect sizes were expressed as partial eta squared (η^2). We used the Bonferroni correction for post-hoc comparisons. A total of 0.05 was chosen as the alpha level. Statistica 12.0 (StatSoft Inc., Tulsa, OK, USA) was used to perform statistical analyses.

Results

Physical Test

The ANOVA on the sprint reaction time showed that the effect of Group ($F < 1$) and Time ($F(1,22)=1.6$, $p=0.218$, $\eta^2=0.071$) were not significant, but was significant the Group x Time interaction ($F(1,22)=4.4$, $p=0.048$, $\eta^2=0.167$). As shown in **Figure 3**, post-hoc comparisons indicated that while in the Con group, the sprint reaction time did not change (pre-test=565 ms \pm 105, post-test=562 ms \pm 103), in the Exp group the reaction time in the post-test (501 ms \pm 97) was shorter ($p=0.026$) than the pre-test (580 ms \pm 120).

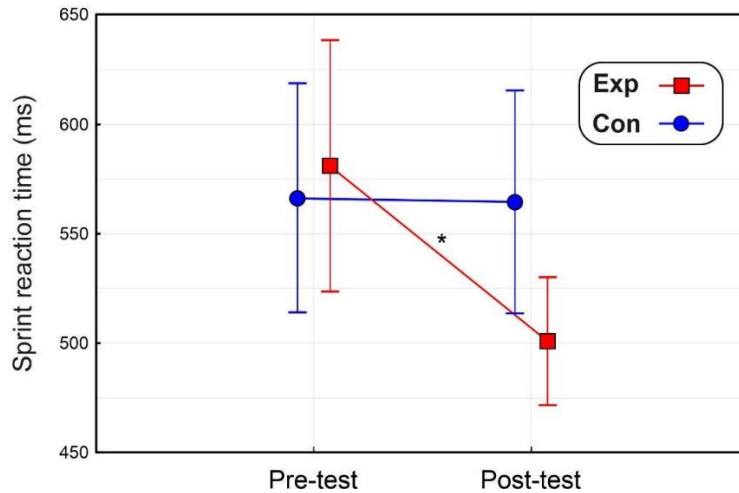


Figure 3. Results of the motor task showing the sprint reaction time. Vertical bars denote 0.95 confidence intervals. * $p < 0.05$.

Cognitive Test

the ANOVA on the RT showed a non-significant effect of Group ($F(1,22)=3.7$, $p=0.067$, $\eta^2=0.145$) and a significant effect of Time ($F(1,22)=8.5$, $p=0.008$, $\eta^2=0.282$). However, the Group x Time interaction was significant ($F(1,22)=6.2$, $p=0.021$, $\eta^2=0.219$). As depicted in **Figure 4a**, post-hoc comparisons indicated that while in the Con group, the RT did not significantly change (pre-test=475 ms \pm 99, post-test=471 ms \pm 97), in the Exp group the RT in the post-test (429 ms \pm 103) was shorter ($p=0.005$) than the pre-test (482 ms \pm 91) and was also shorter ($p=0.018$) than the post-test on the Con group.

ANOVA on accuracy revealed no significant effects of Group ($F(1,22)=1.6$, $p=0.215$, $\eta^2=0.074$). The effect of Time was significant ($F(1,22)=19.6$, $p < 0.001$, $\eta^2=0.889$) indicating less errors in the post-test (2.8% \pm 0.3) than in the pre-test (7.3% \pm 1.5). As shown in **Figure 4b**, the Group x Treatment interaction was not significant ($F < 1$).

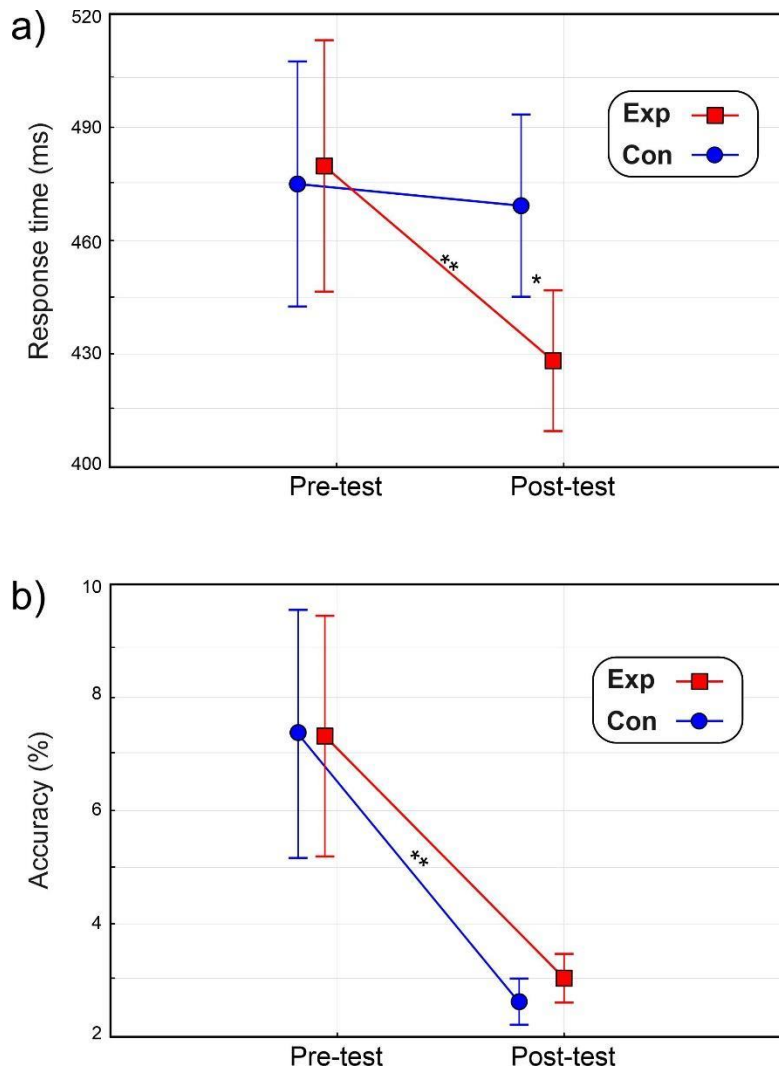


Figure 4. Results in the cognitive task for a) response time, and b) accuracy (error percentage).

Vertical bars denote 0.95 confidence intervals. * $p < 0.05$, ** $p < 0.01$.

ERP Results

Figure 5a shows the pre-stimulus ERP waveforms in the four conditions. **Figure 5b** shows the voltage and topographical distribution in the $-300/0$ ms interval. The BP is the first detectable activity starting from -700 ms and emerging as slow-rising negativity reaching its peak at stimulus onset on medial centroparietal sites. The pN initiated between -620 ms and -600 ms and peaked at stimulus onset on medial prefrontal sites.

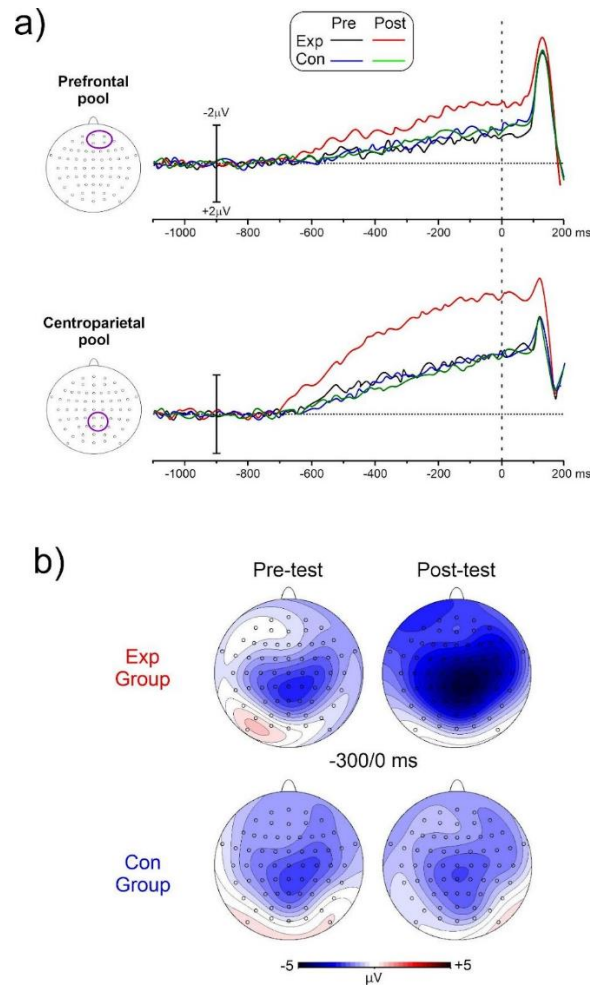


Figure 5. (a) Pre-stimulus ERP waveforms at the prefrontal and centroparietal pools. (b) Scalp voltage topography in the $-300/0$ ms time window from a top-down view.

ANOVA on the pN showed a significant effect of Group ($F(1,22)=5.7$, $p=0.026$, $\eta^2=0.206$) and a non-significant effect of Time ($F(1,22)=2.9$, $p=0.103$, $\eta^2=0.116$). The Group x Time interaction showed a significant tendency ($F(1,22)=4.2$, $p=0.052$, $\eta^2=0.142$). Post-hoc comparisons indicated that the pN amplitude in the post-test of the Exp group ($-2.63 \mu\text{V} \pm 0.84$) was larger ($p=0.048$) than the pre-test ($-1.01 \mu\text{V} \pm 0.71$) and was also larger ($p=0.032$) than the post-test amplitude of the Con group ($0.94 \mu\text{V}$, ± 0.42). The pN amplitudes of the Con group did not significantly differ from each other. **Figure 6a** shows this interaction.

ANOVA on the BP showed a non-significant effect of Group ($F(1,22)=1.9$, $p=0.182$, $\eta^2=0.079$) and a tendency of the Time effect ($F(1,22)=4.0$, $p=0.059$, $\eta^2=0.153$). However, the Group x Time

interaction was significant ($F(1,22)=4.5$, $p=0.045$, $\eta^2=0.170$). Post-hoc comparisons indicated that the BP amplitude in the post-test of the Exp group ($-4.30 \mu\text{V} \pm 2.71$) was larger ($p=0.039$) than the pre-test ($-2.21 \mu\text{V} \pm 2.26$) and was also larger ($p=0.042$) than the post-test amplitude of the Con group ($1.97 \mu\text{V} \pm 0.88$). The BP amplitudes of the Con group did not significantly differ. **Figure 6b** shows this interaction.

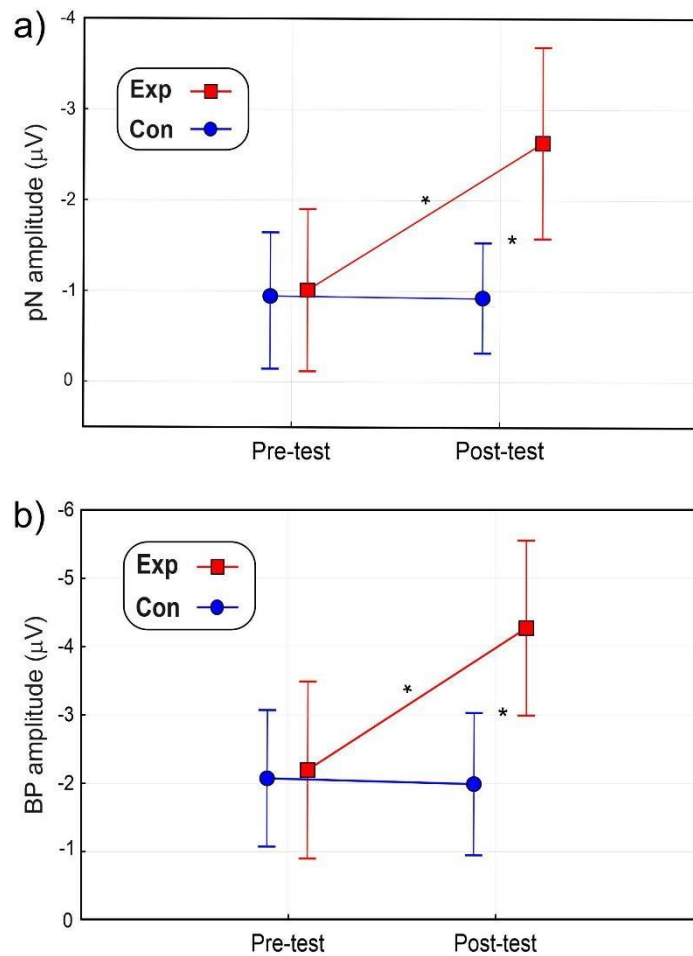


Figure 6. (a) pN amplitude. (b) BP amplitude. Vertical bars denote 0.95 confidence intervals.

* $p < 0.05$

Discussion

In the present study, we tested on healthy participants the effect of a VR-based CMDT training protocol (named VRRT) on their performance in physical and cognitive tasks. In addition, we studied the neural correlates of this effect using ERP measures of anticipatory brain processing in the prefrontal and (the pN) and premotor (the BP) areas. The results showed that following the proposed VRRT the response time for both the 10-meter sprint and the cognitive task was improved by about 14% and 12%, respectively, in only five weeks, while the control group did not show any significant effect. For VR applications in healthy people, this result is novel since no studies found response time improvements in both motor and cognitive tests after a VR treatment. However, the results are in line with two studies (Burin et al., 2019; Burin et al., 2020) comparing the performance in a Stroop task before and after a short session of a VR-based visual training intervention. These studies found that the response time in a Stroop task was shorter after the training. We also confirmed the effectiveness of the CMDT modality in a VR environment with comparable results as found in non-virtual CMDT protocols in the same short amount of time (Lucia et al., 2024; Lucia et al., 2021; Turna, 2020). However, this result is supported by findings (Kim et al., 2019) comparing a standard CMDT protocol with the same protocol but conducted in VR on a group of adults with mild cognitive impairments (MCI). This study reported significant cognitive (e.g., cognitive flexibility, attention, information processing) and motor benefits (e.g., increase in gait speed) following both training protocols. However, the VR training yielded greater benefits in terms of global cognition and instrumental activities of daily living. Related results were found in a study comparing VR-based cognitive training and aerobic and resistance exercise training protocols (Yang et al., 2022). The response accuracy in the cognitive task improved in both groups likely indicating a learning effect. The lack of accuracy effect may be due to the low cognitive demand required by the training that privileged speed and not response accuracy. Indeed, in the tested VRRT, the distinction between two colors to be touched with the right or left hand does not seem to be sufficiently complex to produce significant accuracy benefits in the experimental group. Considering that other CMDT protocols, with higher complexity than the present, found both response speed and accuracy effects (Lucia et al., 2024; Lucia et al., 2021), therefore future studies could test the effect of training with an increased number and shapes of targets that could be mixed with non-targets and distractors. Such modifications would not only increase the chances of obtaining significant accuracy results but also significantly broaden the

scope of application for the training. The neural basis of the behavioral performance effects of the tested VRRT training can be seen by the ERP analysis showing that the experimental group only had a significant increase in motor preparation, as evidenced by the BP components amplitude. Given that, following a careful analysis of the literature, no studies were found on the influence of VR training on the brain activity of the general young adult population. However, (Lucia et al., 2021) observed shorter RT and larger BP in a group of young basketball athletes after 5 weeks of real (non-virtual) CMDT training. The comparable results found here confirm the efficacy of CMDT even in VR. Furthermore, the result of larger BP and shorter RT is consistent with the literature (Di Russo et al., 2019) confirming the association of this motor preparation ERP component with the RT. Concerning the pN component, which reflects attentional and inhibitory preparation for complex tasks, this component showed a trend toward significance with a larger amplitude in the post-test in the experimental group only. This result could indicate that the present VR training, which requires inhibitory and attentional skills to complete the task, may also stimulate these capacities but to a lesser degree and this effect could be covered by task learning. However, the VR training effect on prefrontal areas confirms previous studies on healthy adults (Turna, 2020) and adults with MCI (Kim et al., 2019; Yang et al., 2022). These studies showed modification of functional near-infrared spectroscopy measures over prefrontal areas after virtual training protocols and suggested an increase of neural efficiency in the VR-trained participants. According to the accelerator/braking system proposal (Di Russo et al., 2019), the present training seems to affect the speed/accuracy tradeoff stimulating more the accelerator and less the brake and therefore allowing faster response without limiting accuracy. This pattern of results provides further evidence of the functionality of VR training in positively influencing brain plasticity and it highlights potential uses of VR in enhancing anticipatory cognitive-motor functions in the healthy population. An explanation of how the tested VRRT protocol enhanced these preparatory brain processes may come from studies on CMDT (reviewed in Baumeister et al., 2008). The VRRT, being a dual-task, may produce an over-additive activation of the premotor and prefrontal brain areas that play a key role in managing the concurrent execution of more tasks (Baumeister et al., 2008).

Specifically, the found effects raise considerations about the possible application of this training protocol in various daily life contexts, such as for academic, occupational, and sports achievements. In particular, long-standing research (Boutcher & Zinsser, 1990) and more recent studies (Cooke et al., 2014) emphasized the importance of motor preparation in athletes. These findings are supported by previous electrophysiological studies finding greater cognitive and motor preparation abilities in expert athletes compared to novices (Baumeister et al., 2008). From these studies, it seems evident that motor preparation plays a key role in achieving successful performance. Therefore, future VR training protocols could be designed to allow successful task performance in specific tasks. For example, (Vecchiato et al., 2018) highlights the role played by motor preparation while driving vehicles on the road. Indeed, our brain serves multiple functions beyond the control of body movements. It engages in activities such as sensory-motor transformation, comprehension of actions, decision-making processes related to the initiation and execution of actions, as well as the preparation and planning of intricate movements (Goldberg, 1985; Luppino & Rizzolatti, 2000; Pfurtscheller, 1992; Rizzolatti & Luppino, 2001). Notably, (Rizzolatti & Luppino, 2001) showed that specific neurons in the caudal part of the dorsal premotor cortex activate in response to the onset of movement, others become active during the anticipation of a “go” signal and others respond to the appearance of instructing stimuli. Therefore, what appears evident to date is that specific VR training protocols can significantly influence brain plasticity, creating new possibilities for non-pharmacologic therapeutic intervention in the pathological population (Borgnis et al., 2022) and offering opportunities for cognitive enhancement in the healthy population, such as improving study and work. To increase the validity of the results, further studies should compare VR training with different cognitive and motor training methodologies to identify the optimal training in function of age and work. Finally, the level of perceived embodiment must also be taken into consideration as it significantly influences performance (Juliano et al., 2020) and depends on the limitations of the VR device used.

Conclusion

This study tested the efficacy of a virtual reality-based dual-task cognitive-motor training protocol, named VRRT, in improving physical and cognitive performance in healthy individuals. Results showed significant enhancements in response times for motor and cognitive tasks after only five weeks of VRRT, highlighting the potential of VR technology in increasing human performance.

In addition, while response accuracy in the cognitive task improved in both groups, indicating a learning effect, the VRRT group showed a significant increase in motor preparation, as evidenced by ERP measures of anticipatory brain processing. These results emphasize the functional benefit of VR training in positively influencing brain plasticity and improving anticipatory cognitive-motor function. Importantly, our study fills a significant gap in the literature by demonstrating the benefits of specific VR training in healthy populations, which has significant implications for various domains such as education, employment, and sports performance. In addition, the observed effects raise intriguing possibilities for the application of VR training protocols in various real-world settings. Future research should explore the comparative effectiveness of VR training with other training methodologies, considering factors such as age and occupation. Additionally, the perceived embodiment within the virtual environment should be further investigated as it influences performance and is contingent on the capabilities of the VR device utilized. Overall, this study contributes to the raising body of evidence supporting the potential of VR technology as a tool for cognitive enhancement and performance optimization, both in clinical populations and among healthy individuals. By harnessing the power of immersive virtual environments, we can support new evidence for non-pharmacological therapeutic interventions and foster cognitive growth and development in various daily life area.

4.2 Study 2: Effects of virtual reality-based training for soccer players on anticipatory brain functions and cognitive skills

Abstract: The present study examines the impact of a sport-specific training program based on virtual reality (VR) in young semi-élite soccer players on cognitive performance and on anticipatory brain functions using the event-related potential (ERP) method. In this randomized control trial, the participants were divided into two groups: a control group, which followed a standard soccer training program, and an experimental group, which followed the same training but underwent an additional VR training session once a week. Results indicated that after eight weeks of training, the experimental group only showed a notable enhancement of anticipatory brain activity in the prefrontal cortex as evidenced by a 40% increase in the prefrontal negativity (pN) ERP component. The motor preparatory activity in the premotor cortex indexed by the Bereitschaftspotential (BP) component was comparable between groups before the training and larger in the experimental group after it. Furthermore, the experimental group only showed enhanced cognitive performance improving response speed and accuracy in a discrimination response task. These findings indicate that using VR protocol in conventional soccer training may enhance cognitive anticipatory brain processing underlying top-down cognitive functions. This likely boosted cognitive performance. In conclusion, we confirmed the potential of immersive technologies to facilitate the integration of cognitive training in sports.

Keywords: sport-specific training; virtual reality; EEG; ERP

Introduction. In sports, achieving superior performance necessitates a combination of physiological capacities (e.g., aerobic capacity), psychological attributes (e.g., self-efficacy), and specific skills (e.g., technical and tactical proficiency) (Sarmiento et al., 2018). Researchers investigating the cognitive aspects of sports have predominantly focused on either sport-specific cognitive skills (e.g., Starkes & Ericsson, 2003) or general cognitive functions (e.g., Voss et al., 2010; Williams et al., 2020). It is posited that both general and sport-specific cognitive skills are critical factors contributing to enhanced athletic performance (e.g., Scharfen & Memmert, 2019). Specifically, in open-skill sports such as soccer, a proficient and successful player must process substantial amounts of information rapidly while under mental pressure (Pruna & Bahdur, 2016). Numerous decisions need to be made swiftly and reevaluated dynamically based on the situational demands of the field. This requisite behavior involves specific cognitive anticipatory processes and creative decision-making where both precision and speed are optimized. Consequently, a key characteristic of high-performance athletes is their capacity for unexpected decision-making, which enables them to handle particular performance scenarios more skillfully and makes it difficult for rivals to guess their next move. One of the greatest football players in the world right now is Lionel Messi, who can make unexpected choices that increase the likelihood that his teammates will score goals (Williams et al., 2019). Such cognitive and behavioral adeptness enables the soccer player to effectively "read the game" and form successful anticipatory expectations (Vestberg et al., 2017). In soccer, these mental skills are called "game intelligence" (Stratton et al., 2004). Game intelligence skills are developed when players are provided the opportunity to engage in games-based activities (i.e., replicate the demands of the game) such as small-sided games. During these scenarios they are provided the opportunity to practice visual search, anticipation, decision-making etc. The amount of time that players spend in these activities has been provided in soccer (e.g., Gullich 2019; Andrew et al., 2021; Eather et al., 2023). The importance of game intelligence analysis in sports performance appears to be growing, thanks to coaches' increasing ability to gather increasingly detailed information about their opponents through observational analysis of matches (e.g., studying a team's individual and collective tactical behavior patterns). The ability to understand and operate with this construct would enable coaches and/or staff of professional and amateur soccer teams to offer their athletes increasingly functional and effective training stimuli (Williams & Jackson, 2019). In fact, scientific studies show that athletes' ability to recognize anticipatory cues in their environment, which allow them to predict

what will happen next, placed them in a more favorable position to make unexpected decisions that were less easily predictable by their opponents, thus promoting the development of tactical creativity (Abernethy, Farrow, Gorman, & Mann, 2012; Memmert, 2015a). Specifically, the findings of Roca et al. (2017) highlighted that creative performance is based on distinct perceptual-cognitive processes, which are crucial in facilitating the development of more original solutions. This evidence supports previous research that analyzed the perceptual processes underlying anticipation and decision-making expertise in dynamic open-field game contexts (e.g., Roca, Ford, McRobert, & Williams, 2011; Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts, 2007). This result highlights the association between specific domain expertise and creativity. The ability of creative athletes to adopt more effective visual search strategies in order to identify relevant information in the environment and predict the possible outcomes of a situation likely places them in a more favorable position to plan and select more original and flexible decisions. In addition to the use of anticipatory visual cues, pattern recognition, or knowledge of situational probabilities, creative thinking is considered an additional cognitive skill characteristic of expert performance (Memmert, 2011). These skills mainly involve executive brain functions (e.g., Goldstein & Naglieri, 2014; Barkley, 2012), but these functions are hardly trained in a specific manner in soccer players (Scharfen & Memmert, 2021). The scientific literature on soccer presents many training methodologies that are both quantitatively and qualitatively diverse and often tailored to the needs of individual athletes. Although, multi-component training programs that include multiple kinds of exercises in the same training session (e.g., aerobic/anaerobic/muscular power, speed, strength, flexibility, and agility) are the most used (for reviews see Morgans et al., 2014; Thapa et al., 2021). However, while it is true that current research in the area of sport-specific motor training is abundant, the same cannot be said for the cognitive domain. In another open-skill sport such as basketball, recent studies successfully tested multi-component training programs defined as cognitive-motor dual-task training (CMDT). This training involves a simultaneously balanced combination of motor and cognitive exercises and was found to be more effective than standard training in improving, in a few weeks, both sport-specific and general cognitive performance (Lucia et al. 2022, 2023a, 2023b, 2024a). The integration of specific CMDT protocols into regular training routines in soccer too, could offer significant competitive advantages since Lucia and colleagues' studies have shown that CMDT may improve anticipatory and reactive brain activity subtending the executive functions in prefrontal, premotor, and parietal brain areas. Given these

remarkable findings, the first aim of this research is to expand this training methodology in soccer to determine if athletes could experience the same cognitive benefits presented by Lucia et al. (2022; 2023a; 2023b, 2024a). Specifically, following the training protocol tested here, we hypothesize that significant differences will be found in specific cognitive performance, and therefore in cognitive brain processing as motor preparation, and anticipatory cognitive control.

Even though it had great efficacy, the training system presented by Lucia and colleagues used interactive devices that needed to be positioned on the field rendering the training session (as most training) unrealistic compared to competition. In addition, Dallaway et al. (2021) stated that integrating cognitive methodologies into soccer training might not always be practical due to the limitations imposed by the real training environment, therefore, is not always feasible to introduce cognitive training stimuli on the field. In this context, VR should bypass the limitations of real-world settings. Therefore, we sought to use immersive technology such as virtual reality (VR) to accurately reproduce, during training, any action and situation performed by athletes in competition. VR technology, with its intrinsic characteristics, could overcome the ecological limitations of field training and further validate the CMDT methodology (Casella et al., 2024b). In this context, Wood et al. (2020), drawing on findings in the medical (Gurusamy et al., 2008; Haque & Srinivasan, 2006; Kim et al., 2019; Lerner et al., 2010) and military (e.g., Michalski et al., 2019) fields, conducted a study focusing on the validation of a VR soccer-specific simulator. The performance results of the soccer players on the sport-specific virtual protocol clearly distinguished between elite, semi-elite, and amateur athletes, demonstrating the high transferability of this training mode. Given the numerous advantages offered by VR, this factor should be considered a significant advantage in using virtual systems in sports. In addition, this technology could play a pivotal role in the dissemination of innovative technologies in soccer.

To analyze the influence of VR training on anticipatory processes, neurophysiological techniques such as electroencephalography (EEG), and event-related potentials (ERPs) can be used to detect brain activities with millisecond precision. Due to their superior temporal resolution, ERPs have been effectively used to map the timing of cognitive processes from task preparation to motor execution. In response discrimination tasks (DRTs), such as the Go/No-go paradigm, the anticipatory cognitive and motor functions have been indexed by two main ERP components called prefrontal negativity (pN) and the Bereitschaftspotential (BP) respectively (for data on a large

dataset see Di Russo et al., 2019). The pN has been linked to response accuracy and proactive cognitive functions, such as top-down attention and inhibition within the prefrontal cortex during complex tasks (Di Russo et al., 2107, 2019). The BP is a motor readiness potential reflecting the excitability of the supplementary motor and cingulate areas, emerging before any voluntary action (Shibasaki & Hallett, 2006). Additionally, it has been proposed that these components form the neural basis of a cognitive system for activation/inhibition (braking/accelerating), which influences the speed/accuracy trade-off by predicting and anticipating future actions and events (Di Russo et al., 2019).

Considering that in the mentioned studies on basketball, CMDT interventions found increased preparatory ERP components and improved both general behavioral (response time and accuracy) and sport-specific performances (Lucia et al. 2022, 2023a, 2023b, 2024), we hypothesize that VR-based CMDT training could have the same effect but removing the limitations of putting devices on the training field. Indeed, given its intrinsic characteristics, the VR-CMDT training proposed here could similarly stimulate anticipatory cognitive functions and proactive control processes, which are essential for tasks requiring rapid discrimination and selective response. A recent study of the present group (Casella et al., 2024b) demonstrated that a generic (non-sport-specific) VR reaction training protocol, in non-athletes already increased the pN and BP, therefore we hypothesized that a soccer-specific VR training incorporating the CMDT principles could produce the same effect even in highly trained young soccer players.

Materials and Methods

Participants

The G*power 3.1.9.7 software (Faul et al., 2009) was used to calculate the sample size. For the current mixed 2×2 ANOVA, Cohen's f statistics were used. The estimated effect size ($f=0.28$) was calculated from the minimum partial eta squared obtained in a study using a similar paradigm (Casella et al., 2024). The alpha level was set at 0.05 and the required power ($1-\beta$) at 0.95. With these parameters, the estimated sample size was 30. Thus, 30 young male semi-élite soccer players (mean age: 15.6 years; $SD=0.5$) were enlisted (Swann et al., 2015). The athletes were all enrolled in the sporting club “SS Romulea” of Rome and were part of the under-17 and under-16 teams.

Education and socioeconomic status were also recorded. The following conditions had to be met to be considered for inclusion: no neurological, psychiatric, or medical illnesses; no medication during the experimental session; normal or corrected-to-normal vision; full right-handedness according to the Edinburgh Handedness Inventory (Oldfield, 1971); and unawareness about the purpose of the study. Before taking part in the study, each participant's parents provided informed consent in compliance with the Declaration of Helsinki, which was approved by the University of Rome's "Foro Italico" local ethical council.

Procedure

The participants were equally and randomly assigned to the experimental (Exp) group and the control (Ctr). T-tests ($t(29) < 1$) revealed no differences between the groups concerning age, education, socioeconomic status, or expertise (The Swann classification 3.5 SD = 0.3 and 3.5 SD = 0.3 for Exp and Con, respectively, corresponding to semi-elite level). The Ctr group performed standard soccer training for eight weeks, three days a week (2 hours), plus one day for the official match (2 hours). The training was focused on technical-tactical skills fundamentals. The Exp group followed the same training plan, however, differently from the Ctr group, the last 30 minutes of one weekly training, they performed the VR-CMDT experimental training detailed below. Before and after the eight weeks of training, all the participants were screened using a motor and a cognitive test.

Virtual Reality Training

In the VR training session, athletes were required to perform soccer-specific cognitive-motor drills. Given the relevance of cognitive and executive skills in the game of soccer, this training modality was intended to stimulate specific functions, such as motor preparation, cognitive inhibition, attention, and functional skills such as physical endurance and pacing.

For the implementation of the VR, regarding the hardware instrumentation, the Valve Index VR system (Valve Index Headset, Valve Corporation, Washington, United States) was used, which consists of a head-mounted display, two joysticks, and two base stations for room tracking and movement detection. To integrate the use of feet, a crucial aspect for enhancing the embodiment of the soccer player, two trackers (VIVE tracker 3.0, HTC corporation, Taoyuan City, Taiwan)

were added, which were placed on the athletes' insteps using straps. The used application was Rezzil Index (Mi Hiepa Scout Ltd, Manchester, UK). The software used has already demonstrated its constructive validity, as documented in the literature. In particular, Wood et al. (2020) demonstrated that this simulator is able to significantly distinguish between professional players, academy players, and beginners, based on tasks requiring anticipation, decision-making, and perceptual-cognitive skills, through a diagnostic index (Rezzil Index) that integrates parameters such as passing accuracy, reaction time, adaptability, and performance maintenance under pressure. These results suggest a substantial overlap between the skills trained in the simulation and those required in the real context, confirming that, even in the presence of stimuli that are not perfectly biological, the platform has characteristics that are representative and transferable to real soccer activity. Within this application, the three exercises described below were used.

Color Combo: In this exercise, the players' shoes were divided into four distinct colors. The internal side of the right boot was colored yellow, while the external side was red. The internal side of the left boot was colored blue, and the external side was purple. In front of the athlete was located a ball-launching machine, which consistently released between 1 to 5 balls simultaneously for 1 to 6 minutes depending on the difficulty level. The balls could be of the same colors present on the shoes or could be silver or dark gray (**Figure 1a**). The athlete was required to touch the balls as quickly as possible with part of the foot corresponding to the ball's color. For example, yellow balls were to be touched with the internal side of the right foot, and purple balls with the external side of the left foot (**Figure 1b**). When the machine released silver balls, the player was free to touch them as they preferred.

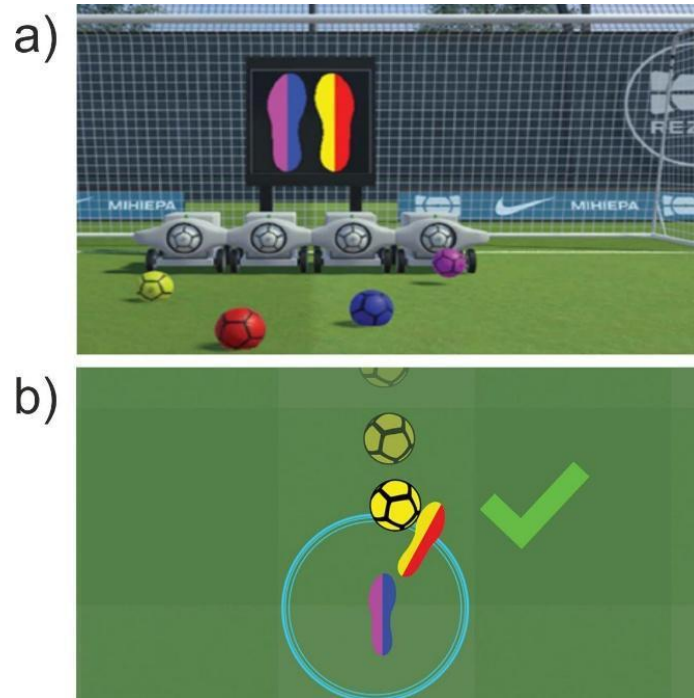


Figure 1: Representation of the Color Combo exercise rules.

Wolfy training: In this exercise, the athlete was required to make soccer-specific decisions as quickly as possible while performing a high-knee run on the spot (delimited by a circle). This exercise consisted of three conditions on which the decisions were based on the speed, body position, and distance of teammates. In the speed condition, 6 player models were shown sprinting away from the user who had to quickly identify and choose the fastest teammate (**Figure 2a, 2b**). In the body position condition, the athlete visualized 6 static teammates along the perimeter of the midfield, each in a different body position, and had to quickly choose the teammate with the best body position for sprinting forward. In the distance condition, the athlete visualized 6 teammates at different distances and had to choose the closest one (**Figure 2c**). Each of the three conditions lasted 1 minute and was repeated three times in each training session. The player had 1 second to make their decision.

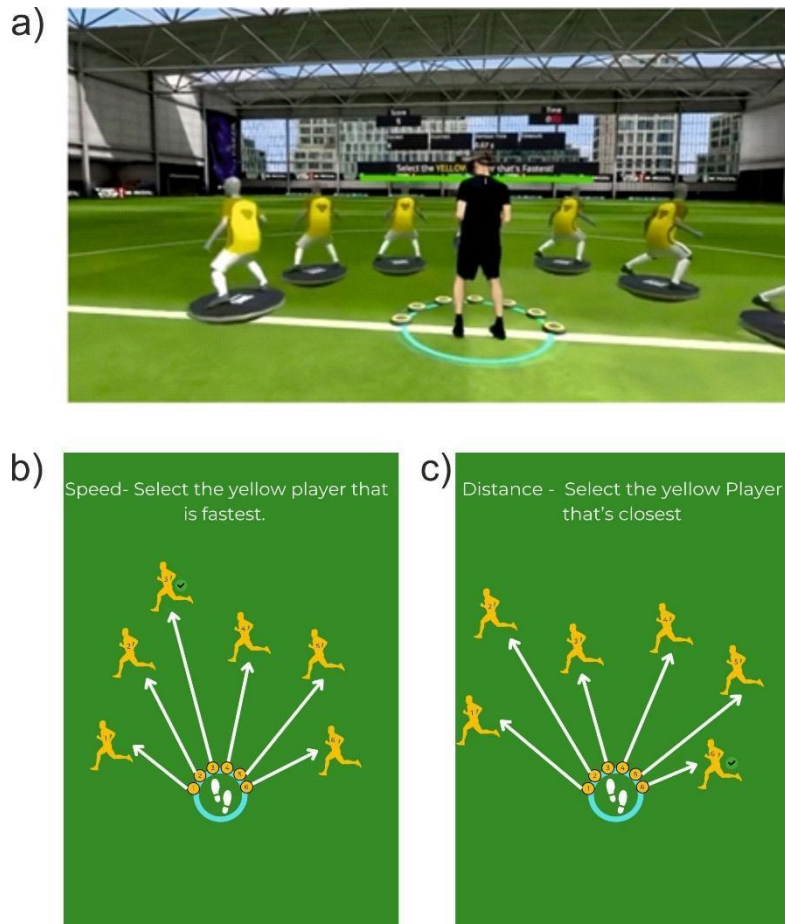


Figure 2: Representation of the Wolfy training exercise rules.

Shoulder Sum: In this exercise, the player faced four full-sized soccer goals with a ball-launching machine between each goal. Each goal was divided into two or three sections each containing a number (**Figure 3**). When the ball was launched to the player, other players, wearing shirts of assorted colors, appeared behind. The participant was required to identify the color of the ball outline once released and, with rapid visual scanning, count the players wearing the shirt of that color. The participant then had to kick the ball into the goal section with that number. As the exercise level progressed, the number of the appearing players and the color variety increased. Thus, the participant had to perform rapid visual scanning behind (right and left), color recognition, arithmetic summation, and kick the ball into the resulting goal section.

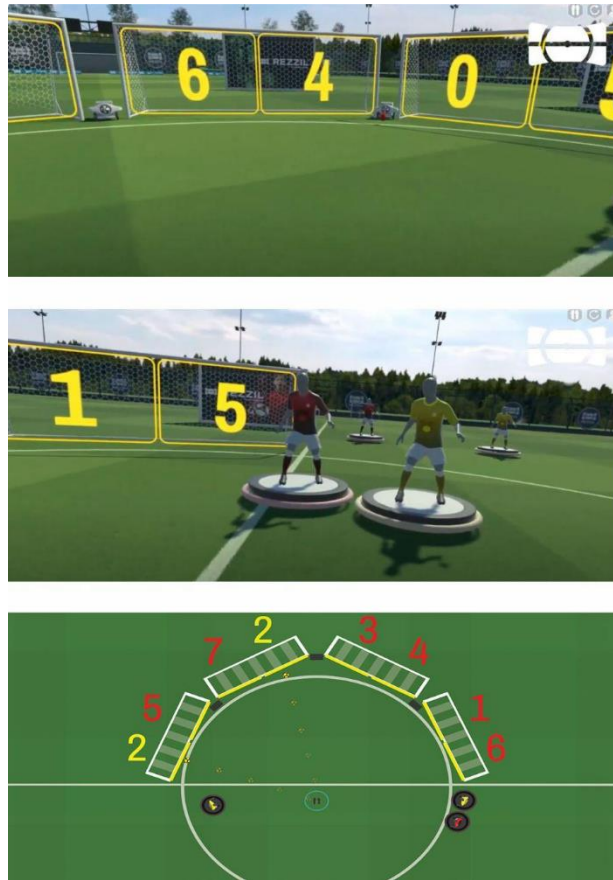


Figure 3: Representation of the Shoulder Sum exercise rules.

Cognitive test

A visuomotor discrimination response task (DRT), also known as Go/No-go task, was carried out. The test was conducted in a semi-dark, soundproof room. The athlete was seated 114 cm in front of a computer monitor and kept his right index finger on a response button. At the start of each trial, a fixation point appeared in the middle of the screen on a black background, and it remained there the entire run. Four square configurations subtending $4 \times 4^\circ$ of the visual field, consisting of vertical and/or horizontal bars, were randomly displayed for 250 ms each, each with an equal probability ($p=0.25$). The interval between stimulus onsets was one to two seconds. Two stimuli were defined as targets and two as non-targets, and the athlete was instructed to press the button as soon as one of the target stimuli appeared; both speed and accuracy were equally emphasized. No response was required to non-target stimuli. The stimuli's order of presentation was random. Every run duration was approximately 2 minutes and was separated by one minute of rest. A total

of ten runs were conducted, yielding approximately 400 trials for each stimulus category. The session duration was approximately 30 minutes. The measured scores were the response time (RT) for hits and the accuracy ratio. Response accuracy was calculated by counting the commission errors (response to non-targets) and was expressed in percentage.

EEG Recording and analysis

During the cognitive test, continuous electroencephalogram (EEG) was recorded using the Recorder 1.2 software and three BrainAmp™ amplifiers—two of which were connected to ActiCap's 64 active sensors. The EEG was processed using the Analyzer 2.3 software (all by BrainProducts GmbH, Gilching, Germany). Electrodes were referenced to M1-M2 electrodes average and followed the 10-10 International System. The EEG signals were digitalized at 250 Hz and were band-pass filtered using a Butterworth zero-phase filter (0.01–60 Hz; second order), and then stored for offline analysis. The electrooculogram (EOG) was recorded using the third BrainAmp amplifier (ExG type), which tracked bipolar eye movements. To record the horizontal EOG, electrodes were placed over the outer canthi of the right and left eyes; to record the vertical EOG, electrodes were placed below and above the left eye. The electrode impedances were maintained below 5 K Ω . The independent component analysis tool in Analyzer 2.2.2 was used to analyze the blink and vertical eye movement artifacts automatically. Following this, the data were automatically submitted to artifact rejection, leading to the elimination of EEG signals whose amplitudes were greater than the threshold of ± 70 μ V. To measure pre-stimulus activity, EEG data was divided into 1300 ms epochs, which started 1100 ms before the stimulus presentation and ended 200 ms after. As a baseline, the first 200 ms (–1100/–900 ms) were utilized. Since the stimulus category was uncertain at the pre-stimulus phase, target and non-target trials were averaged. Intervals and electrodes for statistical analysis were established a-priori using the "collapsed localizer" approach (Luck & Gaspelin, 2017) which required averaging the ERP of all groups and conditions to construct a localizer ERP. The global field power (GFP), which measures ERP spatial variability across all scalp electrodes simultaneously, was computed on the localizer to determine the analysis interval. This was done by selecting the pre-stimulus interval during which the GFP exceeded 70% of its maximum value. In this way, an interval from -300 to 0 ms was selected and the mean amplitude was computed for statistical analysis. Electrodes that exhibited in the localizer ERP amplitudes greater than 70% of the maximum value in the selected

interval were averaged grouping them into spatial pools and submitted to statistical analysis. With this method, two foci of activity were found: a medial centro-parietal pool including the CP1, CPz, CP2, P2, Pz, and P1 electrodes representing the BP components, and a medial prefrontal pool (Fp1, Fpz, Fp2, AF7, AF8) representing the pN.

Statistical Analysis

We assessed for each measure the assumption of normality using the Shapiro-Wilk's W test. The outcomes demonstrated that every measure followed normal distributions since they were all non-significant. The homoscedasticity assumption was evaluated using Levene's test for equality of variance, and no homoscedasticity violation was revealed. Following these preliminary tests, all measurements were put through mixed 2X2 ANOVAs with Group (Exp vs. Ctr) as between factor, and Time (Pre-test vs. Post-test) as within factor. The partial eta squared (η^2) was calculated to report effect sizes. For post-hoc comparisons, we applied Bonferroni correction. The alpha threshold was set at 0.05 overall. Statistical analyses were conducted using Statistica 12.0 (StatSoft Inc., Tulsa, OK, USA). Post-test assessments were conducted within one week of completing the 8-week protocol. Specifically, all participants completed the post-test approximately 48 hours after their last training session (VR or standard) in order to minimize potential immediate carry-over effects and ensure equivalent timing between groups.

Results

Behavioral results

The ANOVA on the RT showed a significant main effect of Group ($F(1,28)=6.3$, $p=0.018$, $\eta^2=0.183$). The Time effect was non-significant ($F(1,28)=1.6$, $p=0.212$, $\eta^2=0.055$). The interaction Group \times Time showed significant effect ($F(1,28)=12.3$, $p=0.002$, $\eta^2=0.305$). Post-hoc comparisons showed that the Exp group only showed reduced RT ($p=0.003$, pre-test=473 ms \pm 49, post-test=436 ms \pm 37). The RT of the Ctr group was similar ($p=0.755$, pre-test=479 ms \pm 44, post-test=477 ms \pm 31). In addition, in the post-test, the RT of the Exp group was lower ($p=0.045$) than that of the Ctr group. The interaction is reported in **Figure 4a**.

ANOVA on the accuracy revealed a significant main effect of Group ($F(1,28)=8.9$, $p=0.006$, $\eta^2=0.242$) and Time ($F(1,28)=31.6$, $p<0.001$, $\eta^2=0.530$). The interaction Group \times Time

($F(1,28)=6.7$, $p=0.015$, $\eta^2=0.194$) was also significant. Post-hoc comparisons showed that the Exp group only showed increased accuracy ($p<0.001$, pre-test= $5.0\% \pm 1.4$, post-test= $1.2\% \pm 0.7$). The accuracy of the Ctr group was similar ($p=0.247$, pre-test= $5.3\% \pm 1.8$, post-test= $3.9\% \pm 1.0$). In addition, in the post-test, the accuracy of the Exp group was lower ($p=0.001$) than that of the Ctr group. The interaction is reported in **Figure 4b**.

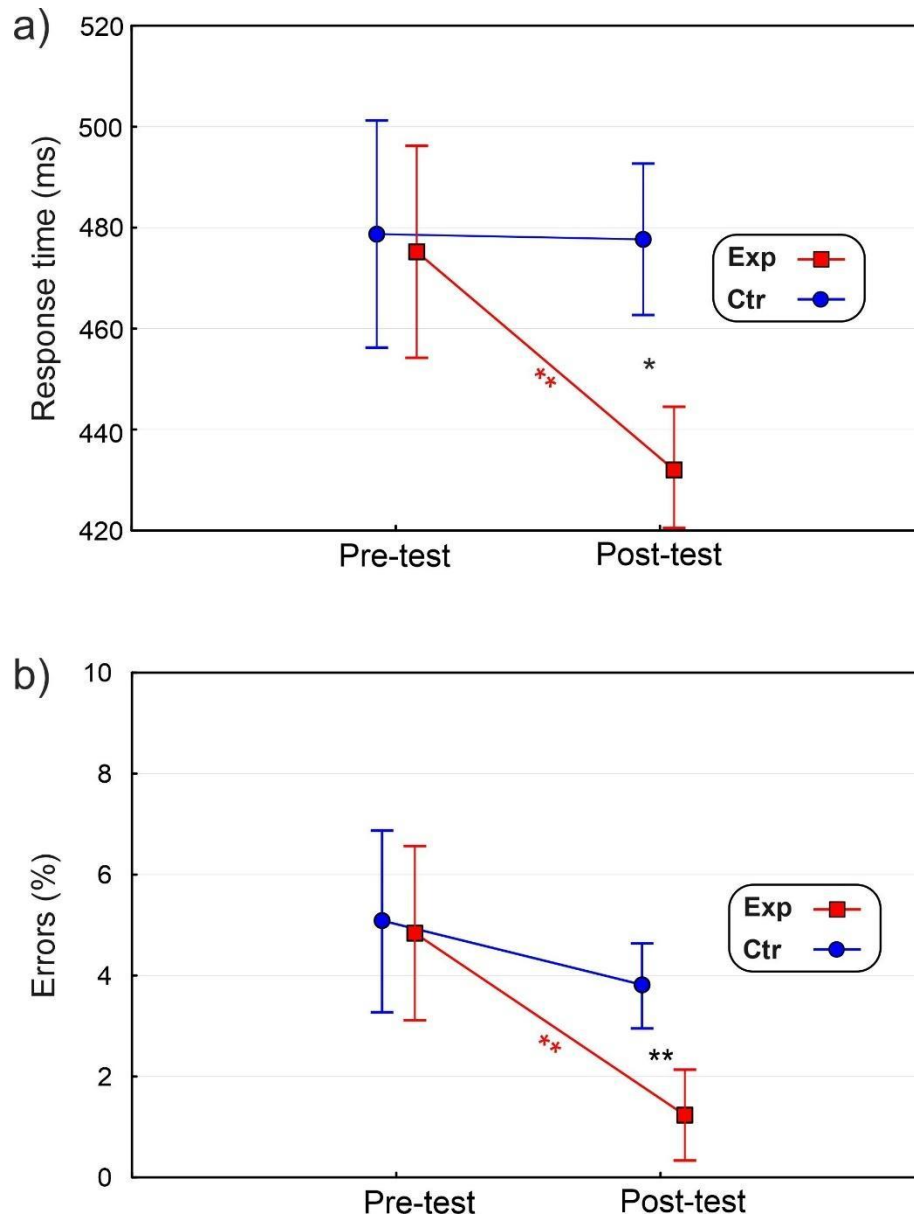


Figure 4: Interaction between Group and Time in the cognitive test. a) Response time (RT), b) Accuracy. The vertical line represents the 0.95 confidence interval. * $p < 0.05$, ** $p < 0.01$.

ERP Results

Figure 5 shows the pre-stimulus ERP waveforms in the four conditions. Figure 6 shows the voltage and topographical distribution in the -300/0 ms interval. The BP is the first detectable activity starting from -700 ms and emerging as slow-rising negativity reaching its peak at stimulus onset on medial centroparietal sites. The pN at about 620 ms and peaked at stimulus onset on medial prefrontal sites.

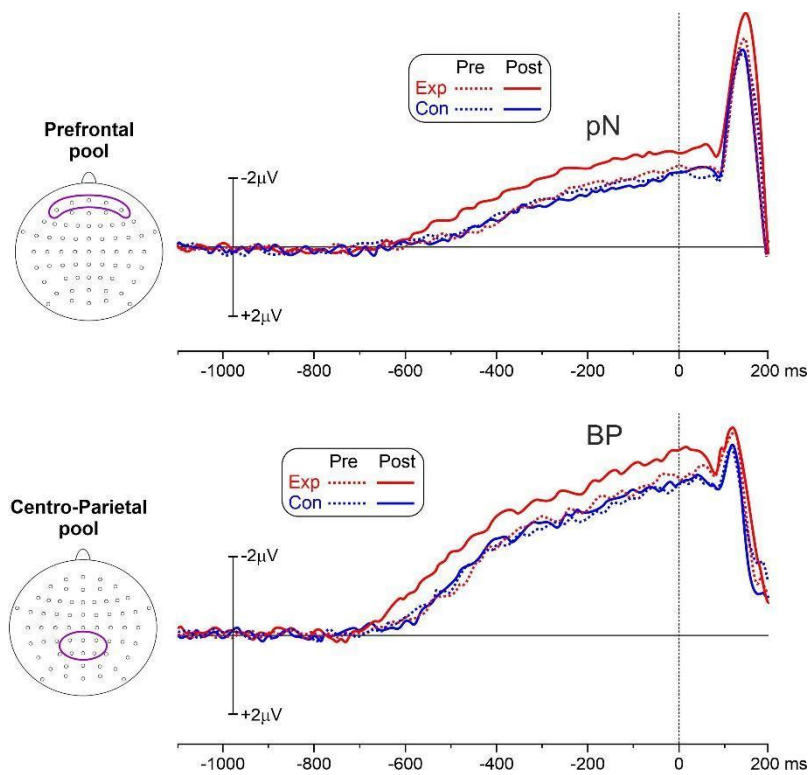


Figure 5: ERP waveform for the Experimental (Exp) and control (Ctr) groups in the pre and post-tests. The waveforms in the upper and lower panels represent the prefrontal and the centro-parietal pools of electrodes marked in the head representation on the left.

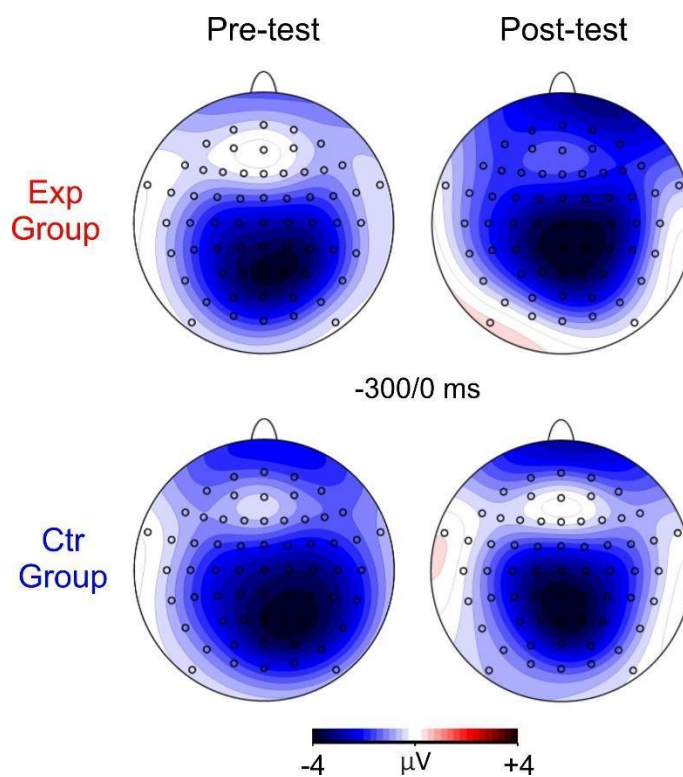


Figure 6: Scalp voltage topography in the interval from -300 to 0 ms for the two groups and tests (top-flat view).

ANOVA on the pN showed a non-significant main effect of Time ($F(1,28)=1.3$, $p=0.261$, $\eta^2=0.045$) and Group ($F(1,28)=1.7$, $p=0.206$, $\eta^2=0.056$). The interaction Group \times Time was significant ($F(1,28)=4.5$, $p=0.042$, $\eta^2=0.139$). Post-hoc comparisons showed that in the Exp group, the pN of the post-test ($2.53 \mu\text{V} \pm 0.86$) was larger ($p=0.020$) than that of the pre-test ($2.04 \mu\text{V} \pm 0.78$). In the Ctr group, the pN did not differ ($p=0.530$) between tests (pre-test= $1.94 \mu\text{V} \pm 0.60$, post-test= $1.78 \mu\text{V} \pm 0.62$). The interaction is reported in **Figure 7a**.

ANOVA on the BP showed a non-significant main effect of Time ($F(1,28)=1.0$, $p=0.312$, $\eta^2=0.035$) and Group ($F(1,28)=0.4$, $p=0.509$, $\eta^2=0.016$). The interaction Group \times Time was significant ($F(1,28)=8.7$, $p=0.006$, $\eta^2=0.237$). Post-hoc comparisons showed that in the post-test, the BP amplitude of the Exp group ($4.03 \mu\text{V} \pm 1.18$) was larger ($p=0.015$) than that of the Ctr group ($2.90 \mu\text{V} \pm 1.11$). In the pre-test (Exp= $3.31 \mu\text{V} \pm 1.34$, Ctr= $3.22 \mu\text{V} \pm 1.50$) the group did not differ ($p=0.097$). The interaction is reported in **Figure 7b**.

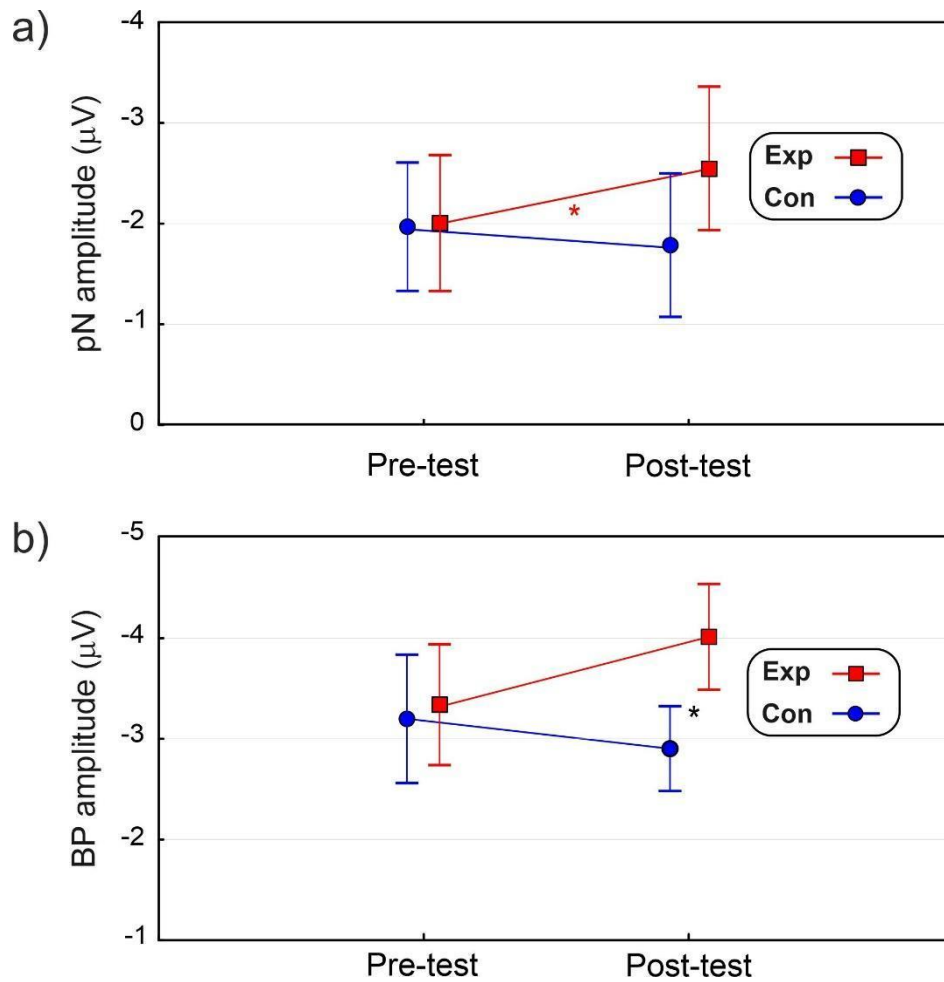


Figure 7. Interaction between Group and Time in ERP. a) pN component amplitude, b) BP component amplitude. The vertical line represents the 0.95 confidence interval. * $p < 0.05$.

Discussion

Based on findings from CMDT studies, using interactive devices placed on the training field (Lucia et al., 2022, 2023a; 2023b, 2024a), we hypothesized that VR sport-specific protocol incorporating the CMDT principles would also lead to increased brain activity associated with task anticipation and therefore improve general cognitive and sport-specific skills in soccer players. Results showed that after the training the experimental group had greater activity than the control group in brain areas involved in proactive attentional control and motor preparation. These effects indexed by the pN and BP amplitudes confirm the body of evidence from Lucia and colleagues' studies (2020,

2021, 2023a, 2023a, 2023b). In addition, behavioral results showed in the experimental group a significant 8% improvement in response time, while the control group showed a markedly lower improvement of just 1%. This finding is consistent with the results reported by Di Russo et al. (2017), who identified a positive correlation between BP and response time. Although, in scientific literature, there are a limited number of studies analyzing soccer players neural correlates, which would allow for a more in-depth commentary on the electrophysiological evidence presented in our research, it is well established that motor preparation plays a crucial role in sports performance (Wang et al., 2020; Makris et al., 2015). Indeed, in a highly dynamic context such as a soccer match, the ability to respond quickly and effectively to multiple situational demands can differentiate between lower and excellent performance (Wang et al., 2020). In this view, successful interaction in dynamic environments involves the ability to predict the outcome of perceived actions and shape anticipatory representations of motor sequences. This ability has been attributed both to general visual processes, responsible for the perception and recognition of environmental elements and to a specialized system focused on the perception of specific movements. Supporting this, neuroimaging and neurophysiological studies have demonstrated that the action observation network involves visual areas as well as pre-motor and motor areas. (e.g., Rizzolatti & Craighero, 2004; Fadiga et al., 2005). Considering the results presented in this study, it is possible that the activation of this network was enhanced in the experimental group. By combining cognitive and motor stimuli, VR training could stimulate motor and pre-motor areas, facilitating the formation of more accurate and faster anticipatory representations of motor sequences. This enhancement in cognitive capacity, experienced after the VR training, could support soccer players in the rapid and effective planning of actions based on the anticipated movements of their opponents (Makris & Urgesi, 2015).

The present ERP results showed that the pN of the experimental group increased by 40% following the training. In contrast, the control group showed a slight deterioration. This increase may have led to an increase in response accuracy in the cognitive task. Specifically, the experimental group significantly reduced by 89% the number of errors whereas the control group only showed a 22% reduction. This finding is supported by previous studies reporting correlations between the pN amplitude and response accuracy (e.g., Di Russo et al. 2017; Lucia et al. 2019). The pN has been associated with cognitive preparation intended as proactive top-down cognitive control as attention and inhibition (e.g., Di Russo et al. 2019). The importance of training cognitive skills in soccer

players has been outlined also by Staiano et al. (2022), who investigated the effect of sequential cognitive-motor training (not dual-task) in professional soccer players. This study found benefits in cognitive skills and performance since cognitive training increased the cognitive load of training without overloading the musculoskeletal system. This further confirms the efficacy of integrating such protocols into the standard training routines of elite athletes. Indeed, in line with several studies (Vestberg et al., 2017; Huijgen et al., 2015), elevated levels of cognitive inhibition and attentional control are essential neural capacities in achieving high-level sports performance. These abilities allow athletes to filter out irrelevant information and focus on key events during competition. In this regard, Wang et al. (2020) highlighted that a greater capacity for attentional control positively correlates with improved athletic performance, particularly in contexts where quick assessment, processing, and execution of complex motor actions are critical. Collectively, these findings suggest that integrating cognitive training protocols into athletes' standard routines could provide significant benefits in terms of attention and accuracy, particularly under conditions of mental fatigue (Pageaux et al., 2014; Cona et al., 2015). Therefore, considering the results presented here and the strong alignment with the existing literature, it seems crucial to integrate VR into athletes' standard programs. In our study, the control group, which was not subjected to the VR treatment, showed no cognitive benefits in the post-test. This finding, as evidenced by Staiano et al. (2022), could be explained by the fact that standard training, which is directly and exclusively focused on athletes' technical and tactical skills, does not offer sufficient cognitive stimulation. Despite the promising results, the present study has some limitations that need to be considered. First, the sample of participants is limited in terms of size and heterogeneity, as it consists exclusively of young male semi-elite soccer players. This limits the generalizability of the results to other categories of athletes, such as females or practitioners of other sports. Furthermore, the relatively short duration of the intervention (eight weeks) may not be sufficient to observe long-term changes in both cognitive and motor skills. Future research should include more diverse samples, extend the duration of the interventions, and investigate the long-term effect of the proposed methodologies. Moreover, future studies should test the transferability of the VR-CMDT benefits to the playing field, for example on the number of goals and assists or other performance indexes of the soccer performance.

4.3 Study 3: The effect of sport-specific virtual reality training for soccer players on cognitive performance and related brain processing

Abstract: This study aimed to evaluate the effects of sport-specific training in virtual reality (VR) on perceptual and cognitive abilities and their neurophysiological correlates in young soccer players. Twenty-four young semi-elite soccer athletes were assigned to an experimental (Exp) or control (Ctr) group. Participants' cognitive functions were tested before and after an 8-week standard soccer training using a visuomotor cognitive task during electrophysiological (EEG) recording. The Exp group in the last 30 minutes of each training session performed the VR training aimed at improving processing speed, cognitive flexibility, and working memory. While the cognitive task allowed to measure response speed and accuracy, the EEG permitted to measure the event-related potential (ERP) evoked by the cognitive task. Results showed that both response speed and accuracy were improved in the Exp group only, and this effect could be explained by increased sensorimotor integration in prefrontal areas indexed by the prefrontal P1 (pP1) component and increased post-perceptual cognitive processing as decision-making in parietal areas indexed by the P3 component. These results support the effectiveness of VR in enhancing cognitive functions, highlighting the technology's potential for innovative training for soccer.

Keywords: virtual reality, sport training, cognition, soccer

Introduction

A proficient soccer player must be able to quickly handle an extensive amount of information under mental strain. Numerous choices need to be made rapidly and then reassessed considering the field demands (Vestberg et al., 2017). In these situations, enhanced perception, attention, sensorimotor integration and decision-making could permit optimal precision and speed to perform successfully. According to various authors, the athlete's capacity to provide a range of solutions that are appropriate and unique derives from efficient cognitive processing (e.g., Sternberg & Lubart 1999; Runco 2014; Memmert & Roca 2019). For instance, Vestberg, Gustavson, Maurex, Ingvar, and Petrovic (2012) found that high division soccer players performed better than lower division players on several cognitive function tests. Therefore, for successful performance, soccer players require not only technical and physical capabilities but also specific cognitive abilities (see Memmert, 2017a for a review). Decision-making is critical for successful performance, and it is well known that this cognitive skill is based on efficient perceptual and attentional capacities (e.g., Roca et al., 2021). Specifically, perception, sensorimotor integration and attention allow efficient environmental scanning to locate relevant cues while filtering out distractions. Research has shown that expert soccer players exhibit efficient visual search strategies, characterized by a considerable number of brief fixations directed at key areas of the field, such as unmarked teammates, open spaces, and opponents (Vaeyens et al., 2007a, b; Roca et al., 2013; Roca et al., 2018). These visual search strategies are linked to enhanced selective attention processes, helping athletes focus on task-specific knowledge structures essential for decision-making (Henderson, 2003; Cardoso et al., 2021). These perceptual-cognitive skills, cultivated through thousands of practices and reflection, support swift and accurate decisions under high-pressure situations during the competition (Ericsson, Krampe, & Tesch-Römer, 1993; MacMahon & McPherson, 2009). Ultimately, technical proficiency, sensory-motor skills, and advanced cognitive functioning underpins the complex demands of soccer, reinforcing the notion that top performance hinges on the interplay between mind and body (Baker & Young, 2014; Memmert et al., 2010).

Given the findings presented, it is evident that cognitive brain processing has a positive influence on the sports performance of competitive soccer players. For this reason, there is an increasing interest in evaluating the effectiveness of training aimed at boosting these cognitive processes. Most of the protocols proposed for perceptual-cognitive processes have been developed using a cognitive skills component approach, by training athletes' fundamental visual and cognitive skills

in sport-unspecific contexts (i.e., domain-generic) (Heilmann et al., 2024). For example, Savelsberg et al. (2010) have observed a significant increase in visual search strategy following a computer-based perceptual training intervention. Another widely applied training-program associated with this approach is called NeuroTracker™ (NT) 3 dimensional (3D) multiple-object tracking (MOT) (Faubert, 2013). It appears to produce significant improvements in the trained skill (i.e., pursuit of multiple objects simultaneously), but not on perceptual-cognitive functions such as visual clarity or inhibition (Scharfen & Memmert, 2021). In general, studies focusing on athletes with a domain-generic approach to cognitive training have shown inconsistent effects on performance in cognitive tasks (Scharfen & Memmert, 2019), and often the effects are not transferred into other contexts. For example, Harris et al. (2018) reported difficulty in transferring the effects of cognitive training to sporting tasks. Generalization of functions trained in different domains is known as skill transfer: transferring skills between related domains is called “near” transfer, while “far” transfer occurs weakly or unrelately between domains and it is much less common than “near” transfer (Heilmann et al., 2024). In domain-generic cognitive training, in order to transfer the specific skill trained to a particular sport context or situation, a far transfer is required.

Unlike cognitive skills component approach, the expert-performance approach investigates the athlete’s visual and cognitive expertise employing sport-specific stimuli in sport-specific contexts (e.g. decision-making in sport-specific settings, domain-specific) (Scharfen & Memmert, 2021), facilitating near transfer. In this theoretical framework, Schumacher et al. (2020) found that peripheral reaction abilities can be improved by a soccer-specific perceptual-cognitive on-field, combining a sport-specific and a juggling task. These considerations suggest that non-sport-specific cognitive training may have limited applicability to real-game scenarios, highlighting the need for methodologies that integrate cognitive training within the perceptual and motor demands of sport-specific contexts.

Nevertheless, there is a scarcity of research aimed at identifying a sport-specific and situational training methodology for enhancing such cognitive functions. One possible explanation, as suggested by Staiano et al. (2022), may be the limitations imposed by the training environment. In soccer, it is not always feasible to implement a cognitive training protocol that is sufficiently intensive and tailored to the needs of competitive athletes. Ehmann et al., (2022) used the Multiple Object Tracking (360-MOT) device in which screens were placed around the player to create an

immersive environment. The functions of the device are aimed at enhancing peripheral vision, divided attention, and rapid decision-making. The experimental group subjected to training with this tool showed significant improvements in perceptual and cognitive functions. However, the results of the tests were not substantial enough to be transferred to the real game. In this context, a suitable method to address the gap in sport-specific cognitive training methodologies is the implementation of protocols based on virtual reality (VR). VR offers unique characteristics that make it an ideal tool for enhancing cognitive functions. Its ability to create immersive, highly controlled, and replicable environments allows for the manipulation of game scenarios in ways that are difficult to achieve in traditional training settings (Faubert, 2013; Fadde & Zaichkowsky, 2018). For soccer players, this means being exposed to realistic but adjustable challenges that target perceptual and cognitive processes essential for high-pressure decision-making (Romeas et al., 2016). Furthermore, VR enables the integration of dynamic stimuli and cognitive-motor dual tasks, which have been shown to improve selective attention, sensory awareness, response times, and therefore decision-making efficiency (Neumann et al., 2018; Michalski et al., 2019). Unlike standard training methods, VR allows athletes to rehearse specific scenarios repeatedly, offering opportunities to develop predictive abilities, tactical creativity, and problem-solving skills in a safe yet demanding environment (Bideau et al., 2010).

Considering these intrinsic advantages, the application of VR-based training protocols has the potential to enhance perceptual and cognitive processing of soccer players. We hypothesize that the immersive nature of VR, combined with its adaptability to the needs of athletes, could provide innovative training for optimizing performance-related perceptual and cognitive functions in competitive sports.

A suitable method to investigate the effect of VR training on brain activity associated with perceptual and cognitive processes is the use of electroencephalogram (EEG) and event-related potentials (ERPs). Known for their high temporal resolution, these neurophysiological techniques allow researchers to investigate neural underpinnings of sensory and cognitive processes in real time during task execution. In sensorimotor cognitive tasks, the main ERP components evoked in response to visual stimuli are known as the P1, N1, and P3 components. Previous studies have identified the P1 component as an early marker of sensory response to visual cues, which aids for rapid orienting to relevant stimuli (e.g., Di Russo et al., 2006; Hillyard & Anllo-Vento, 1998; Luck & Kappenman, 2012). This initial processing is essential for filtering sensory input and prepares

the brain for more selective attentional responses. Subsequently, the N1 component has been associated with early attentional control, especially to focus on task-relevant cues (e.g., [Di Russo et al., 2006](#); [Wang et al., 2020](#)). Post-perceptual cognitive functions, such as decision-making, are reflected by the emergence of the P3 component. The P3 is widely considered a marker of cognitive processing such as task evaluation and decision-making, reflecting the brain's capacity for rapid stimulus categorization and response selection ([Polich, 2007](#); [Wang et al., 2020](#)). Furthermore, P3 amplitude is sensitive to the degree of stimulus-response compatibility and cognitive conflict resolution ([Kok, 2001](#); [Polich, 2007](#)), the level of the P3 amplitude may provide an implication of the efficient stimulus evaluation and the concrete level of the difficulty of the task design for training.

In addition to these well-known ERP components, another early process supporting perception and actions such as sensorimotor awareness is reflected by the prefrontal P1 (pP1). The pP1 component has been associated with sensorimotor integration, representing the brain's ability to align perceptual awareness with motor planning, a process critical for coordinating rapid and accurate responses (e.g., [Gonçalves, et al., 2018](#); [Perri et al., 2017, 2018](#); [Di Russo et al., 2019](#)) as in dynamic sports environments. While numerous studies highlight that sports practice influences ERP components (e.g., [Chueh et al., 2017](#); [Liu et al., 2017](#); [Wei et al., 2017](#); [Lucia et al., 2023a, b](#)), there is limited research exploring these components within the structured frameworks of VR training, especially in soccer.

Given the cognitive demands of soccer in terms of perception, attention, sensorimotor awareness and decision-making (e.g., [Roca et al., 2011](#); [Vaeyens et al., 2007](#)), this study aims to investigate the effects of a sport-specific VR cognitive training on perceptual-cognitive processing and its neurophysiological correlates in young soccer players. Since VR protocol involves dynamic and immersive scenarios requiring continuous attentional engagement and rapid visual information processing, it could be possible to observe an enhancement both in early visual perception, reflected by an increased amplitude of P1 component, and in attentional focus on relevant stimuli, expressed by an increased N1 component. Additionally, considering that VR-based drills require both visual awareness and stimulus categorization for motor response selection in realistic game-like conditions, we hypothesize that VR training will strengthen sensorimotor integration, indexed by an increase in the pP1, and enhance decision-making processes, as reflected by a larger P3 component. These neurophysiological changes should translate into faster response times and

improved accuracy in cognitive tasks, reflecting a reinforcement of high-level perceptual-cognitive abilities crucial for soccer performance.

Materials and Methods

Participants

Using the G*power 3.1.9.7 program (Faul et al., 2009), the sample size was determined. The current mixed 2×2×2 ANOVA was conducted using Cohen's f statistics. The least partial eta squared found in a study employing a comparable paradigm was used to compute the estimated effect size ($f=0.6$) (Casella et al., 2024). The necessary power ($1-\beta$) was set at 0.95 and the alpha level at 0.05. The expected sample size under these conditions was 24. As a result, 24 young male soccer players were recruited (mean age: 15.6 years; $SD=0.5$). All the athletes were members of the under-17 and under-16 squads of the Rome-based sporting club "SS Romulea."

The athletes' level of proficiency was assessed using the Swann classification (Swann et al., 2015). Socioeconomic position and education were also noted. To be eligible for inclusion, a participant had to meet the following requirements: completely right-handedness as measured by the Edinburgh Handedness Inventory (Oldfield, 1971); no neurological, psychiatric, or medical conditions; no medication during the experimental session; normal or corrected-to-normal vision; and ignorance of the study's goal. In accordance with the Declaration of Helsinki, each participant's parents gave their informed consent prior to participation in the study, which was authorized by the "Foro Italico" local ethics council at the University of Rome.

Procedure

The participants were equally and randomly assigned to the experimental (Exp) group and the control (Ctr). T-tests ($t_{(29)} < 1$) revealed no differences between the groups concerning age, education, socioeconomic status, or expertise (The Swann classification 3.5 ± 0.3 was identical in the two groups corresponding to semi-elite level). The Ctr group performed standard soccer training for eight weeks, three days a week (2 hours), plus one day for the official match (2 hours). The training was focused on technical-tactical skills fundamentals. The Exp group followed the same training plan; however, differently from the Ctr group, the last 30 minutes of one weekly training, they performed the VR training detailed below. Before and after the eight weeks of training, all the participants were screened using a cognitive test during EEG recording.

Virtual Reality training

The VR training protocol, fully described in Appendix, included three exercises designed to increase specific cognitive functions, such as decision-making, working memory, and cognitive flexibility (Tab. 1). Virtual scenarios have the characteristic of representing a soccer-specific ecological situation, immersing the athlete in soccer fields with goals, teammates and interactions with balls. Each exercise lasted 6-10 minutes with pauses interleaved. The Valve Index virtual reality system (HTC business Taoyuan, Taiwan) was utilized as hardware instrumentation. It includes two joysticks, a virtual reality headset, and two base stations for movement detection and room tracking. Two HTC Valve Trackers 3.0 were added and strapped onto the athletes' insteps to incorporate the use of feet, which is an essential component for improving the embodiment of the soccer player.

VR scenario	Description	Cognitive processes	ERP Components
Feature Discrimination and Working Memory Drill	Perceptual discrimination based on color and ball movement. It requires a rapid and selective sensorimotor response.	Selective attention and perceptual-motor integration	P1, N1, pP1
Multidirectional Process, Tactical Adaptation and Cognitive Flexibility Drill	Simulates game situations with the need for visual scanning and tactical adaptation. Requires assessment of the position of teammates and rapid strategic decision making.	Sensorimotor integration and decision making	pP1, P3

Speed, Accuracy and Decision Making Drill	Training on selecting the best teammate based on speed, position and distance. Promotes quick reaction and decision making under pressure.	Decision-making and stimulus categorization	P3
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Tab. 1. Schematic description of VR Cognitive Training

Cognitive test

A visuomotor decision making task was carried out in a soundproof, semi-dark area. The athlete held his right index finger on a response button as he sat 114 cm away from a computer monitor. A fixation point was placed in the center of the screen on a black background at the beginning of each trial, and it stayed there for the duration of the run. Four square configurations subtending $4 \times 4^\circ$ of the visual field, consisting of vertical and/or horizontal bars, were randomly displayed for 250 ms each, each with an equal probability ($p=0.25$). There was a one to two second lag between stimulus onsets. The athlete was told to hit the button as soon as one of the target stimuli appeared. Two stimuli were designated as targets, and two as non-targets. Non-target stimuli did not demand a reaction. Equal emphasis was placed on accuracy and speed. The order in which the stimuli were presented was arbitrary. Each run lasted roughly two minutes, with a one-minute rest period in between. Ten runs were performed in all, resulting in roughly 400 trials for per stimulus group. The session lasted for about half an hour. The accuracy ratio and response time (RT) for hits were the scores that were measured. Commission mistakes (reaction to non-targets) were counted to determine accuracy, which was then expressed in percentage.

EEG Recording and analysis

During the decision-making test, continuous electroencephalogram (EEG) was recorded using the Recorder 1.2 software and three BrainAmp™ amplifiers—two of which were connected to ActiCap's 64 active sensors. The EEG was processed using the Analyzer 2.3 software (all by BrainProducts GmbH, Gilching, Germany). Electrodes were referenced to averaged M1-M2

electrodes and followed the 10-10 International System. The EEG signals were digitalized at 250 Hz and were band-pass filtered using a Butterworth zero-phase filter (0.01–60 Hz; second order) and then stored for offline analysis. The third BrainAmp amplifier (ExG type), which monitored bipolar eye movements, was used to record the electrooculogram (EOG). Electrodes were positioned above the outer canthi of the right and left eyes to record the horizontal EOG, and beneath and above the left eye to record the vertical EOG. The impedances of the electrodes were kept below 5 K Ω . The blinks and eye movement were automatically eliminated using Analyzer 2.2.2's independent component analysis tool. After that, the data were automatically subjected to artifact rejection, which resulted in the removal of EEG signals with amplitudes still higher than the ± 70 μ V threshold. To measure post-stimulus activity, EEG data was divided into 1200 ms epochs, which started 200 ms before the stimulus onset and ended 1000 ms after it. As a baseline, the first 200 ms (–200/0 ms) were used. Target and non-target trials were averaged separately.

Using the "collapsed localizer" approach (Luck & Gaspelin, 2017), which requires averaging the ERP of all groups and conditions to generate a localizer ERP, intervals and electrodes for statistical analysis were determined a-priori. To calculate the analysis interval for statistical analysis, the global field power (GFP), which measures ERP spatial variability across all scalp electrodes, was calculated on the localizer. As previously done (e.g., Lucia et al., 2023), the GFP was used to individuate the components to be analyzed selecting all peaks present in the GFP. To select the interval around the peak to be analyzed, the time range in which the GFP exceeded 80% the peak was included. Similarly, the electrodes that displayed amplitudes exceeding 80% of the maximum value within the chosen interval were also averaged and grouped into spatial pools. As shown in Figure 1, with this method, three foci of activity were found at 124-152 ms, 192-224 ms, and 432-552 ms in which the mean amplitude was calculated. For a better identification of the ERP components present in those intervals, the voltage scalp topography was used. In the first interval the bilateral parieto-occipital P1 was present. In the second interval the bilateral parieto-occipital N1 and the medial prefrontal P1 (pP1) were present. In the third interval the medial parietal P3 was present. The spatial pools were: PO9, PO7, PO3, PO4, PO8. PO9 for the P1 and the N1 (parieto-occipital pool). AF1, AFz, AF2, F1, Fz, F3 for the pP1 (prefrontal pool). C1, Cz, C2, CP1, CPz CP2 for the P3 (central pool).

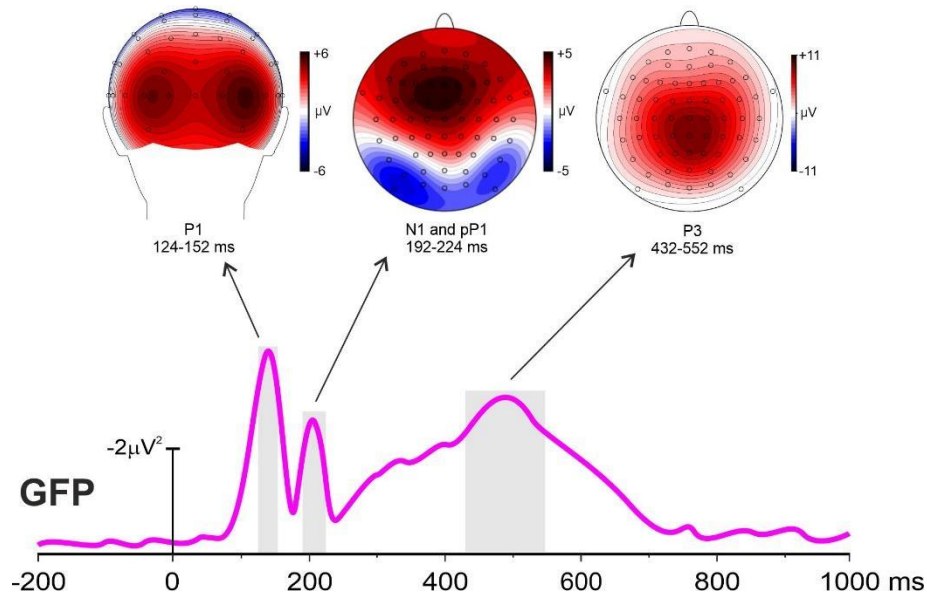


Figure 1. Global field power (GFP) of the collapsed localizer and scalp topography in the selected intervals.

Statistical Analysis

We assessed for each measure the assumption of normality using the Shapiro-Wilk's W test. The outcomes demonstrated that every measure followed normal distributions since they were all non-significant. The homoscedasticity assumption was evaluated using Levene's test for equality of variance, and no homoscedasticity violation was revealed. The behavioral measures were submitted to 2×2 ANOVAs with Group (Exp vs. Con) and Time (Pre-test vs. Post-test) as factors. The P1, N1, pP1 and P3 ERP components amplitude was submitted to 2×2×2 ANOVAs with Group, Time, and Trial (Target vs. Non-target) as factors. The partial eta squared (η_p^2) was calculated to report effect sizes. For post-hoc comparisons, we applied Bonferroni correction. The alpha threshold was set at 0.05 overall. Statistical analyses were conducted using Statistica 12.0 (StatSoft Inc., Tulsa, OK, USA).

Results

Behavioral results

ANOVA on the RT showed a significant effect of Group ($F_{(1,28)}=6.3, p<0.05, \eta_p^2=0.183$), while the Time effect did not reach statistical significance ($F_{(1,28)}=1.6, p=0.212, \eta_p^2=0.055$). The interaction Group × Time was significant ($F_{(1,28)}=12.3, p<0.05, \eta_p^2=0.305$). Post-hoc comparisons showed that,

while in the Exp group RT was significantly reduced ($p < 0.01$, Pre-test=473 ms \pm 49, Post-test=436 ms \pm 37), in the Ctr group no significant difference was found ($p = 0.755$, Pre-test=479 ms \pm 44, Post-test=477 ms \pm 31). Moreover, in the Post-test, the RT of the Exp group was lower ($p < .005$) than in the Ctr group. The interaction is reported in **Figure 2a**.

ANOVA on the errors revealed that Group ($F_{(1,28)} = 8.9$, $p < 0.05$, $\eta_p^2 = 0.242$) and Time ($F_{(1,28)} = 31.6$, $p < 0.001$, $\eta_p^2 = 0.530$) had significant effects. The interaction Group \times Time ($F_{(1,28)} = 6.7$, $p < 0.05$, $\eta_p^2 = 0.194$) was also significant. Post-hoc comparisons showed that the Exp group only showed decreased errors ($p < 0.01$, pre-test=5.0% \pm 1.4, post-test=1.2% \pm 0.7). In contrast, in the Ctr group was measured similar errors ($p = 0.25$) between Pre-test (5.3% \pm 1.8) and Post-test (3.9% \pm 1.0). In addition, in the Post-test, the errors of the Exp group was lower ($p < 0.01$) than the Ctr group. The interaction is reported in **Figure 2b**.

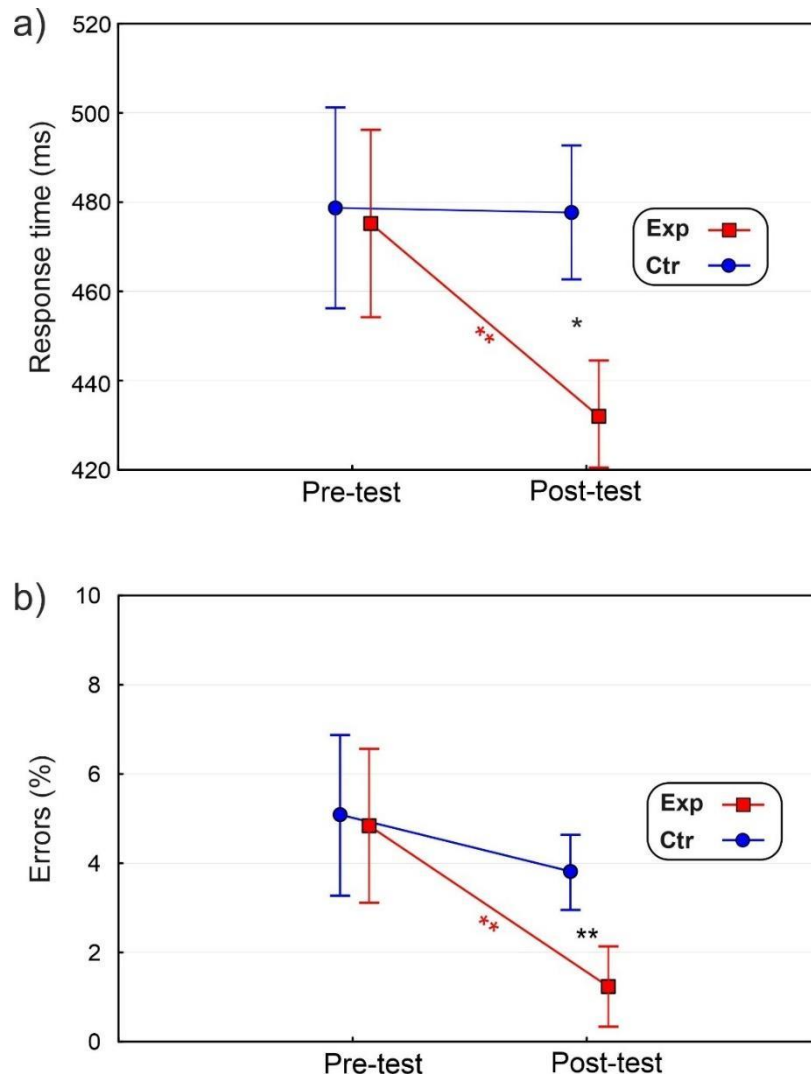


Figure 2: Interaction between Group and Time in the cognitive test. a) Response time (RT), b) Errors. The vertical lines represent the 0.95 confidence interval. * $p < 0.05$, ** $p < 0.01$.

ERP Results

Figure 3 shows the ERP waveforms of the two groups, before and after the treatment and for the two trial types. The studied components (P1, N1, pP1 and P3) are labeled close to their peaks.

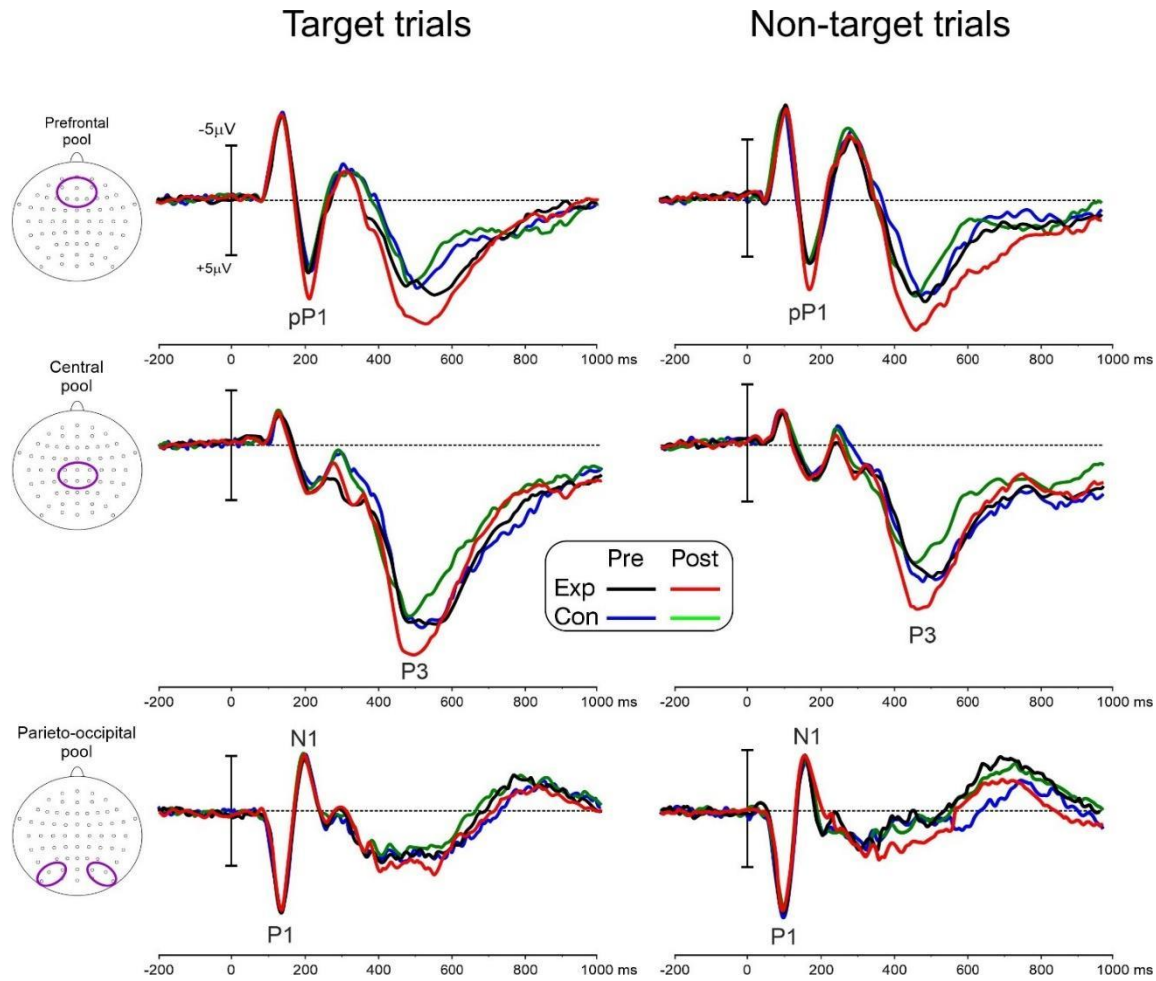


Figure 3: ERP waveform of the experimental (Exp) and control (Con) groups, before (Pre) and after (Post) the training. ERP for target and non-target trial were shown on the left and right side of the figure, respectively. The head representation on the left indicates the electrode included into three spatial pools considered.

ANOVAs on the P1 and N1 did not show any significant effects ($F < 1$). The ANOVA on the pP1 showed a significant effect of Trial ($F(1,22)=30.9$, $p < 0.01$, $\eta^2=0.584$) indicating with larger

amplitude for target than non-target trials. The effect of Group, Time, Trial \times Time and Trial \times Group interaction were not significant ($F < 1$). The interaction Time \times Group was significant ($F(1,22)=7.9$, $p < 0.05$, $\eta^2=0.264$). Post-hoc comparisons showed that in the Post-test, the pP1 amplitude of the Exp group ($6.69 \mu\text{V} \pm 2.37$) was larger ($p=0.01$) than in the Pre-test ($4.39 \mu\text{V} \pm 3.09$). Conversely, in the Ctr group, no significant difference was found ($p=0.21$) between Post-test ($4.23 \mu\text{V} \pm 2.49$) and Pre-test (4.58 ± 2.75). In addition, in the post-test, the Exp group showed a larger pP1 (0.04) than the control group. This interaction is reported in Figure 4a. The 3-level interaction (Group \times Trial \times Time) was significant ($F(1,22)=6.8$, $p < 0.05$, $\eta^2=0.237$) but did not provide additional information.

The ANOVA on P3 exhibited significant effects of Trial ($F(1,22)=45.5$, $p < 0.01$, $\eta^2=0.674$) with larger amplitude for target than non-target trials. The effects of Group ($F > 1$) and Time ($F(1,22)=1.7$, $p=0.20$, $\eta^2=0.073$) were not significant. The interaction Time \times Group ($F(1,22)=8.4$, $p < 0.01$, $\eta^2=0.275$) was significant. Post-hoc comparisons revealed that in the Post-test the P3 amplitude of the Exp group ($10.41 \mu\text{V} \pm 5.35$) was larger ($p < 0.01$) than in the Pre-test ($7.76 \mu\text{V} \pm 4.70$). On the other hand, the Ctr group showed a non-significant reduction of P3 amplitude ($p=0.28$) between Post-test ($7.81 \mu\text{V} \pm 4.65$) and Pre-test (8.10 ± 5.17). In addition, in the post-test, the Exp group tended to have a larger P3 (0.06) than the control group. This interaction is reported in Figure 4b. The interaction Trial \times Group was significant ($F(1,22)=8.1$, $p < 0.01$, $\eta^2=0.268$) but did not provide additional information. The Trial \times Time and the Trial \times Time \times Group interactions were not significant ($F < 1$).

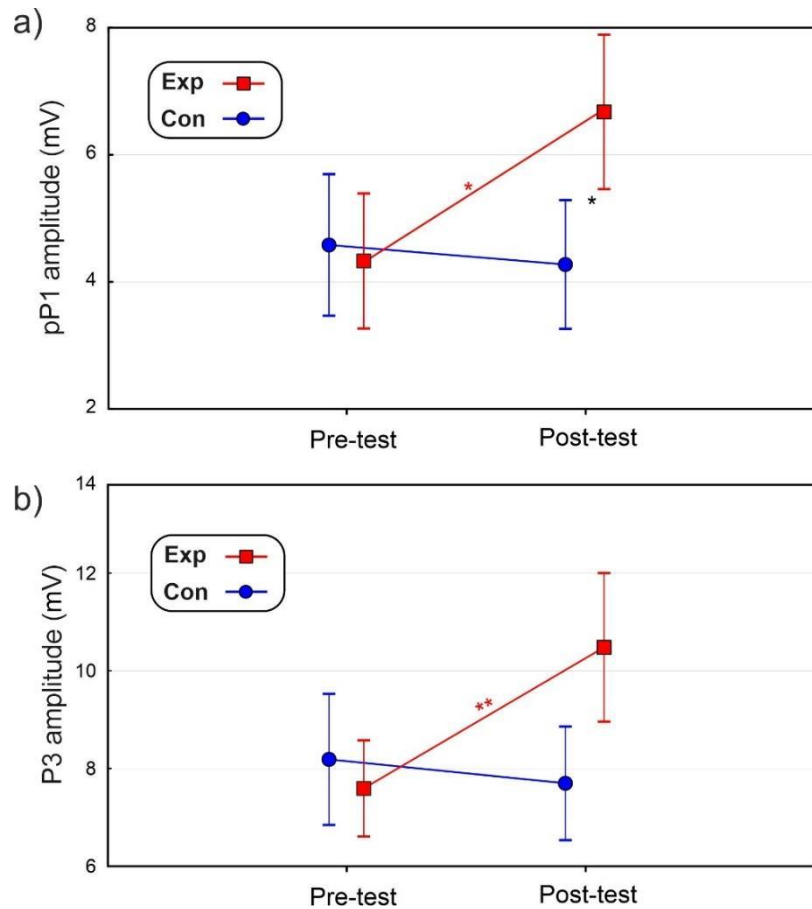


Figure 4: Interaction between Group and Time. a) pP1 amplitude), b) P3 amplitude. The vertical lines represent the 0.95 confidence interval. * $p < 0.05$, ** $p < 0.01$.

Discussion

Considering the extensive scientific evidence about the positive relation between cognitive functions and sport performance (e.g., Finkenzeller et al., 2023; Vestberg et al., 2012; 2017; Huijgen et al., 2015) and the limited amount of situational and sport-specific cognitive protocols for soccer (Romeas et al., 2016; 2019; Moreira et al., 2021), this research settled as its main goal to test the influence of a sport-specific VR cognitive training on athletes' cognitive skills and their brain correlates.

Results showed that the experimental group performance in the cognitive task improved after the VR training compared to before, displaying faster response time (about 8%) and increasing response accuracy from 95% to 98.8%. While before the training the two groups were comparable, after it, the experimental group outperformed the control group in both speed and accuracy.

On a neurophysiological level, this effect could be explained by increased pP1 peaking at about 200 over prefrontal areas in the VR training only. This component has been associated with coordination of rapid and accurate responses, sensorimotor integration and the alignment of visual awareness on motor control (e.g., Di Russo et al., 2019; Gonçalves, et al., 2028; Perri et al., 2017, 2018). This suggests an enhanced capacity for integrating perceptual input with goal-directed motor action, a critical skill for executing complex cognitive functions such as decision-making and strategic planning in dynamic sports like soccer. Several studies (Alfonso et al., 2012; Roca et al., 2011; 2013; Vaeyens et al., 2007a; 2007b; Williams et al., 2004) aimed at analyzing those cognitive processes that, in dynamic and changing contexts such as those of sport-open skills, seem to drive the so-called creative behaviors under time-constrained and high-pressure conditions. Another boosting effect of the VR training was found on later cognitive processes indexed by the P3. This component is a well-known marker of post-perceptual cognitive processing such as task evaluation and decision-making also reflecting stimulus categorization and response selection (Polich, 2007; Wang et al., 2020). Furthermore, numerous studies (Carlson et al., 2009; Gao et al., 2023; Lucia et al., 2023) point out that P3 is related to so-called creative decision-making, which is crucial for achieving optimal performance in competitive sports. Some studies related this cognitive capacity with soccer performance (Vestberg et al., 2012; 2017; Huijgen et al., 2015). Consistently with this perspective, Roca et al. (2018) highlighted that the ability to generate unexpected and creative technical gestures in competition turns out to be a key determinant to expert performance in sports. In professional sports, since of constant and continuous motor training, athletes' physical, technical-tactical skills reach nearly the same excellent level of performance, creative skills appear to be able to offer significant benefits to sports performance (Reilly et al., 2010).

Contrary to expectation, the P1 and N1 components did not show significant increases; this result could be explained by several factors. The VR scenarios proposed for training, while requiring rapid decision-making and dynamic environmental scanning, may not have sufficiently stimulated attentional focus regarding the low-level visual features of the stimulus, needed to increase early perceptual processes. Indeed, P1 component is an early marker of sensory response to visual cues, aiding in orienting to relevant stimuli (e.g., Di Russo et al., 2006; Hillyard & Anllo-Vento, 1998; Luck & Kappenman, 2012) and the N1 component has been associated with early attentional control, especially to focus on task-relevant cues (e.g., Di Russo et al., 2006; Wang et al., 2020);

the immersive nature and the task demands of VR protocol may have distributed attentional resources over multiple stimuli, preventing selective reinforcement of sensory filtering mechanisms at an early stage. This would suggest that high-demanding cognitive training could produce improvements in late cognitive processing only. However, it should also be considered that among the three exercises proposed in the protocol, only “Feature Discrimination and Working Memory Drill” aims at reinforcing early perceptual processes, due to the focus on the color of the stimulus needed for response (see Appendix). Thus, the combination of cognitive-perceptual demands regarding both late and early processes in the proposed protocol may have masked the results on early components. In fact, there is evidence of sport-specific perceptual-cognitive training protocols that increase peripheral perception skills in soccer players (Schumacher et al., 2020). This is why future research should separate protocols for early and late processes to clarify the benefits of VR trainings.

Within the theoretical framework of expert-performance approach, the present study enriches the current literature on the effectiveness of sport-specific cognitive training in increasing cognitive processes trained. While domain-general training has problems with transferability to sport-specific contexts (Harris et al., 2018; Scharfen & Memmert, 2021; Romeas et al., 2016), some studies such as the present one investigate sport-specific training effects assessing perceptual-cognitive processes with non-specific cognitive tasks. Using this approach, Heilmann et al. (2024) observed a lack of improvement in cognitive flexibility, inhibition and working memory tasks after sport-specific training, suggesting limited transferability from domain-specific to domain-general. In contrast, the present results show significant improvement in late cognitive processes, underscoring the possibility of domain-general improvement through sport-specific training. This inconsistency between studies could be due to the fact that the VR protocol allows immersiveness in the environment with the implementation of first-person (egocentric) viewpoints, that increase the representativeness of decision-making tasks (Petit et al., 2008). Another important element to enhance the cognitive level of young soccer players is the intensity of training that induces higher perceptual-cognitive demands comparable to the ones required during the match: are recommended the use of technical and tactical drills that focus on the speed-agility under time pressure, to increase the speed of execution and the subsequent strong modification on the attentional level and on coordination skills (Reilly et al., 2010; Vestberg et al., 2012).

Therefore, the sport-specific immersiveness of virtual reality and the implementation of exercises with high-cognitive and motor-response demands could be necessary features for the effectiveness of cognitive training protocols in soccer players.

The present result aligns with the perception-action cycle model described by Habekost et al. (2024), which identifies three key functional stages in soccer players' cognitive adaptability: situational assessment, action selection, and feedback-based learning. These stages highlight the dynamic interaction between perceptual, motor, and cognitive mechanisms, enabling elite athletes to make rapid and effective decisions under dynamic conditions. Skills such as pattern recognition, attentional focus, and working memory emerge as critical components of this process, supporting creativity and strategic flexibility during gameplay.

Grounded in these premises, our study's findings acquire relevance, since the integration of such VR training protocol into the standard routines of young soccer players appears to have positively influenced the athletes' neural activation. Specifically, it seems that those cognitive processes that would ensure action-oriented perceptual abilities on the field, optimal creative decision-making abilities, efficient cognitive are improved following the proposed training. Although the existing literature offers limited research on similar training approaches, our findings align with emerging studies emphasizing the role of cognitive processes in sports performance. For example, Lucia et al. (2021; 2023a; 2023b) demonstrated cognitive-motor dual-task training positively influences neural activity and motor skills, which are critical for high-level performance, in basketball athletes. These results contribute to the growing body of evidence exploring the cognitive mechanisms underlying elite athletic performance, moving beyond traditional focuses on tactical, technical, and physiological efficiency (Scharfen & Memmert, 2019). Furthermore, given the situational limitation presented by Staiano et al. (2022) regarding the difficulty of adding cognitive stimuli in the context of soccer training, we believe, through the VR training protocol presented here, that we have offered an interesting solution to fill this gap and provide a sport-specific cognitive training methodology.

In conclusion, this study's showed the impact of sport-specific VR training on semi-elite soccer players' brain activity and performance. The experimental group's improving of late cognitive processes implies that incorporating the proposed protocol into routine training regimens may provide a significant edge in efficient cognitive processing, especially in high-stress, dynamic

scenarios that are frequently encountered in competitive games to maximize performance on the field. These findings offer encouraging proof that the tested VR training can aid in the acquisition of critical cognitive abilities that characterize elite athletes.

To ensure wider applicability across a variety of athletic populations, future research should examine the long-term benefits of such training interventions and their application across other sports. Additionally, the lack of improvement in early cognitive processes highlights the need of investigate the effectiveness of training by distinguishing perceptual processes and late cognitive ones, with the aim of enabling customized VR protocols in order to optimize individual athlete development

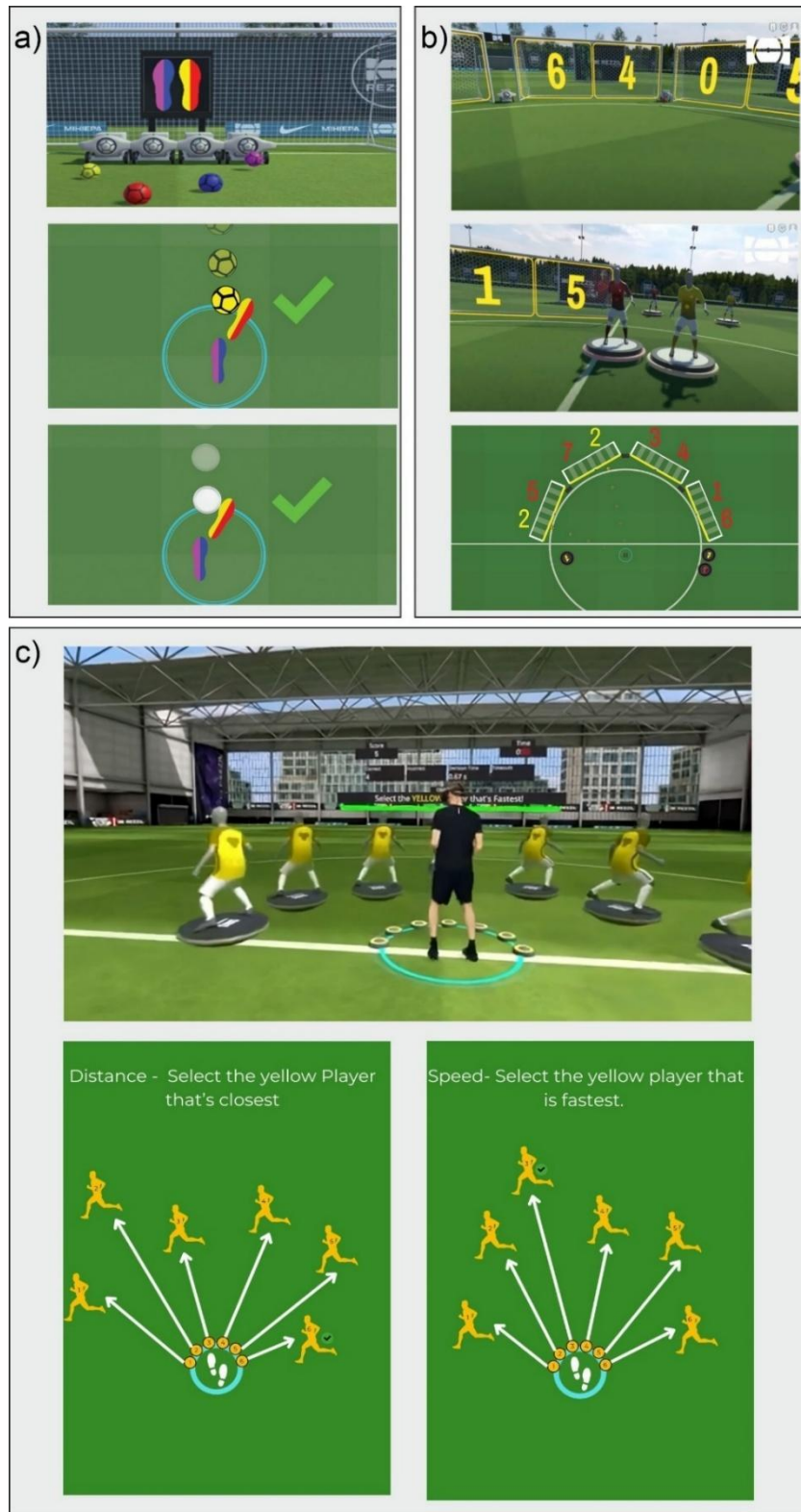
Appendix

Feature discrimination and working memory drill (Supplementary Figure 1a): The players' shoes were separated into four colors for this activity. The right boot is red on the outside and yellow on the inside. The outside and the inside of the left boot were purple and blue, respectively. Depending on the degree of difficulty, a ball-launching machine in front of the athlete would continuously release one to five balls at once for one to six minutes. The balls could be silver or dark gray, or they could be the same color as the shoes. The athlete had to interact with the balls as fast as they could using the foot section that matched the color of the ball. For instance, the internal side of the right foot was supposed to touch yellow balls, whereas the external side of the left foot was supposed to touch purple balls. The player could touch the silver balls as they pleased when the machine released them. The athlete was required to suppress their touch and avoid the dark gray balls when they were launched.

Multidirectional processing, tactical adaptation and cognitive flexibility drill (Supplementary Figure 1b) In this workout, the player had to face four full-sized soccer goals, with a ball-launching machine positioned between them. Each goal was divided into two or three areas, each marked with a number in the center and a colored trim along the border. As the ball was delivered, a few figures wearing jerseys in different colors appeared behind the athlete's left and right shoulders. The player was required to perform a visual scan of the figures and identify the jersey color that appeared most frequently. Subsequently, the athlete had to kick the ball into the goal area corresponding to the number and color matching the majority group. The number of players that appeared increased as the exercise level scaled. To kick the ball into the resulting goal section, the

player had to complete visual scanning (right and left), majority color recognition, and arithmetic summation.

Speed, accuracy, and decision-making drill (Supplementary Figure 1c): In order to complete a high-knee run on the spot (bound by a circle), the athlete had to make soccer-specific judgments as fast as possible. Decisions in this exercise were made based on three criteria: teammates' distance, body position, and speed. The participant had to rapidly identify and select the fastest teammate in the speed condition, which involved visualizing six colleagues running ahead. In the body position condition, the athlete had to rapidly select the teammate with the optimal body position for sprinting forward after visualizing six static teammates around the midfield, each in a distinct body position. In the distance condition, the participant had to select the nearest of six teammates they could see at varying distances. Every training session included three repetitions of each of the three conditions, each lasting one minute. The player's decision-making time was one second.



Supplementary Figure 1: Representation of the three exercises used for the intervention. a) Exercise for feature discrimination and working memory, b) Exercise for multidirectional

processing, tactical adaptation, and cognitive flexibility, and c) Exercise for speed, accuracy, and decision-making.

4.4 Study 4: Identifying electrophysiological signatures of proactive and reactive cognitive brain processing of professional dancers

Abstract: This study investigated the electrophysiological correlates of proactive and reactive brain processing and behavior associated with a visuomotor cognitive task of professional dancers to test the effect of dance practice on their cognitive functions. To control for the physical activity practice effects, dancers were compared with non-dancers matched for physical activity level. Behavioral data showed that dancers were more accurate than controls, and they had comparable response times. This effect was paralleled by the analysis of event-related potential (ERP), showing dancers compared to controls larger cognitive preparation in the prefrontal cortex (PFC), indexed by the prefrontal negativity (pN) ERP component. This may indicate a more intense top-down attentional control of the upcoming task. Dancers also showed reduced early sensory processing (P1 component) and less intense stimulus-response mapping (pP2 component), suggesting more efficient reactive processing in sensorial and associative brain areas. In contrast, the pP1 component was enhanced in dancers, likely reflecting superior sensory-motor integration, a pivotal function in choreographic demands. No difference emerged in the P3, signaling a similar cognitive load for the two groups. The results outline a peculiar neurofunctional profile of professional dancers, relying on intense cognitive anticipatory control and optimized proactive processing, allowing them superior response precision in sensory-motor performance. Further studies are needed to fully understand the specific trajectories of brain plasticity found here associated with dance practice.

Keywords: Dance, Brain, ERP, Anticipatory and reactive cognition

Introduction

Dancing is a universal expression of human movement, characterized by the integration and coordination of motor, perceptual, and cognitive aspects (e.g., Bläsing et al., 2012). Correct execution of individual movements and bodily expressiveness define the performance of professional dancers. For instance, dancers perform intricate movement sequences converting audio and visual cues into physical activity. To synchronize their movements in an ensemble, dancers must pay close attention to other. Dancing requires multiple neurocognitive functions to be performed simultaneously, including fine motor control, cognitive and motor anticipation, perception, attention, visuomotor imagination, time synchronization, and motor memory (Bläsing et al., 2012; Golomer et al., 1999).

Considering the remarkable impact of the cognitive and motor aspect on dancers' performance, a series of studies in the field of motor control and cognitive sciences have delved into the features that seem to discriminate dancers from non-dancers and athletes (Bruyneel, Mesure, Paré, & Bertrand, 2010; Chatfield, Krasnow, Herman, & Blessing, 2007). Specifically, it seems that dance training improves sensorimotor control processes that underlie both dynamic and static balance. For instance, classically trained dancers can keep specific postures for longer periods, have great postural control (Rein, Fabian, Zwipp, Rammelt, & Weindel, 2011), and step with greater vertical alignment than non-dancers (Chatfield, Krasnow, Herman, & Blessing, 2007). Moreover, dancers have superior balance skills when compared to non-dancers (Golomer et al., 1999; Golomer, Dupui, & Monod, 1997; Golomer, Dupui, & Monod 1997) or when compared to less experienced dancers (Bruyneel et al., 2010). Not only that, but such studies have also investigated how dancers synchronize their movements with music and other dancers. A key component of maintaining synchronization in dancing appears to be attention, as attentional distractions reduce timing accuracy in dancers (Moncla et al., 2008a,b).

Whereas considerable focus has been directed towards the motor outcomes of dance training, fewer investigations have examined the neurophysiological mechanisms that support this proficiency. Neuroimaging studies have found that professional dancers exhibit enhanced activity in brain areas associated with action recognition and memory (e.g., Burzynska et al., 2017; Wang et al., 2024). Electroencephalography (EEG) and event-related potential (ERP) studies examined brain processing of professional dancers during the observation of video dance stimuli. Results,

summarized in the systematic review of Angelopoulou et al. (2022), showed that professional dancers compared to non-dancers had an earlier alpha band peak EEG frequency (associated with cognitive preparedness) in sensorimotor regions, and increased synchrony of the theta, beta, and gamma bands (supporting communication between brain regions). ERP data (Orlandi et al., 2017, 2020) showed in dancers an enlarged P3 component in frontoparietal areas and later positivity, indicating more intense late cognitive processing during the observation of ballet steps. In a discrimination response task, using non-dance-related stimuli, dancers displayed a marked top-down task processing reflected by increased P3 amplitude, indicating stronger control of endogenous orientation of attention, and decreased P1 amplitude, suggesting suppression of low-level sensory input to reduce interference with endogenous task (Isoglu-Alkac 2018). Overall, these studies indicated that dancers may have increased visuomotor cognitive skills due to neuroplasticity induced by long-term practice, allowing them to process their actions more easily. All these studies investigated reactive brain processing to stimuli in cognitive tasks, but only one investigated the proactive brain processing of dancers, which is the anticipatory/preparatory brain activity developing before the stimulus presentation. This study (Amoruso et al., 2014) found larger generalized preparatory activity in expert dancers while watching dances compared to beginners and non-dancers, suggesting that dance practice may increase action anticipation and comprehension. No data on task anticipation using neutral stimuli is available. Moreover, no ERP study to date has compared dancers to non-dancers matched for physical activity to control for domain-specific cognitive adaptations independent from those produced by physical training.

The present study aims to identify electrophysiological signatures of proactive and reactive cognitive processing in professional dancers compared to non-dancers, practicing a similar amount of physical activity. To generalize the results, we used a visuomotor cognitive task with non-dance-related stimuli. To achieve this aim, we recorded high-density EEG during the task, and we evaluated the ERP components associated with anticipatory control, stimulus processing, and evaluation, as well as behavioral performance. Specifically, in discrimination response tasks (DRT), anticipatory cognitive and motor functions are represented by two ERP pre-stimulus components: the prefrontal negativity (pN) and Bereitschaftspotential (BP), initiating 700-800 ms before the stimulus onset and gently arising as a negative ramp up to stimulus occurrence. The pN has been associated with cognitive preparation, including top-down attention and inhibition in the prefrontal cortex (PFC) during complex tasks. Large pN amplitude has been associated with

improved response accuracy (e.g., Di Russo et al., 2017, 2019). The BP is an index of motor readiness indicative of the progressive excitability of the supplementary motor area (SMA) and cingulate regions, before any voluntary movement (e.g., Shibasaki & Hallett, 2006). Large BP amplitude has been associated with improved response speed (e.g., Di Russo et al., 2017, 2019). Di Russo et al. (2019) have proposed that these components may form the neural basis of a cognitive system that controls proactive activation/inhibition (accelerating/braking system), which influences behavioral performance in terms of speed/accuracy trade-off by to improve prediction and anticipation of upcoming actions and events (see also Bianco et al., 2017). Furthermore, considering that previous studies on reactive (post-stimulus) ERP components investigated only the P1 and the P3, here we tested all the detectable components in order to obtain a wider picture than before about reactive brain processing of dancers. Therefore, we investigated the early P1 and N1 that are recognized as the primary ERPs elicited by visual stimuli and originating from bilateral extrastriate areas. Prior research has recognized the P1 component as an early indicator of sensory reaction to visual stimuli. Peaking at 100-140 ms after the stimulus onset, the P1 is thought to facilitate swift orientation towards pertinent signals. This initial processing is essential for filtering sensory input and prepares the brain to implement spatial attention (e.g., Di Russo et al., 2006; Hillyard & Anllo-Vento, 1998; Luck & Kappenman, 2012). Subsequently, the N1 component, peaking at 140-180 ms, has been associated with early attentional control, especially to focus perception on task-relevant cues (e.g., Di Russo et al., 2006; Wang et al., 2020). Post-perceptual cognitive functions, such as decision-making, are mirrored by the appearance of the P3 component. The P3, peaking at 300-600 ms, is widely considered a marker of post-perceptual cognitive processing such as task evaluation and decision-making, reflecting the brain's capacity for rapid stimulus categorization and response selection (e.g., Polich, 2007; Wang et al., 2020). The P3 amplitude is sensitive to the degree of cognitive conflict resolution and stimulus-response compatibility (Kok, 2001; Polich, 2007).

In addition to these well-known ERP components, three other processes supporting perception and actions from anterior (prefrontal and frontal) brain regions can be detected. The prefrontal N1 (pN1), P1 (pP1), and P2 (pP2) components (for data on a large dataset see Di Russo et al., 2019). The pN1, peaking at 100-130 ms, has been associated with sensory awareness, intended as stimulus relevance detection, and early top-down attentional modulation. It is thought to reflect sensory monitoring at the executive level, particularly in tasks requiring rapid discrimination and response

control (e.g., Perri et al., 2014; Di Russo et al., 2019; Bianco et al., 2021). The pP1, peaking at 160-200 ms, has been linked to sensorimotor integration, which refers to the brain's capacity to synchronize motor planning and perceptual awareness. This process is essential for coordinating rapid and accurate reactions, such as in fast-paced athletic settings (e.g., Gonçalves et al., 2018; Perri et al., 2017, 2018; Di Russo et al., 2019). Finally, the pP2, peaking at 250-400 ms, is thought to be indicative of post-perceptual conflict processing and response evaluation. The pP2 is particularly sensitive to task demands involving stimulus-response mapping, since it is needed to classify the present information by matching it with the relative response. This component has also been linked to response-related processing of sensory evidence accumulation when decision-making is required (e.g., Di Russo et al., 2019; Gonçalves et al., 2018; Gonzalez-Rosa et al., 2013; Perri et al., 2015; Perri & Di Russo, 2017). Being the pP2 associated with the comparison of target and non-target stimuli, is appropriately described by the target minus non-target trials difference wave (e.g., Di Russo et al., 2019). All the components have been localized in frontal brain areas as the anterior insular cortex, combining ERP measures with functional magnetic resonance imaging (Di Russo et al., 2016; Ragazzoni et al., 2019; Sulpizio et al., 2017).

Considering this wide-ranging ERP analysis, at the proactive (pre-stimulus) level, we expect dancers to exhibit increased amplitude of the prefrontal negativity (pN), a component associated with cognitive preparation, inhibitory control, and top-down attentional orientation in the PFC (e.g., Di Russo et al., 2017, 2019). These functions are particularly emphasized in choreographic training, which requires sustained selective attention and anticipatory processing of movement (Bläsing et al., 2012). In contrast, the Bereitschaftspotential (BP) - an index of generalized motor readiness preceding voluntary movement (e.g., Shibasaki & Hallett, 2006) - may not significantly differ between the two groups, as both engage in physically demanding activities. This component reflects pre-movement motor excitability, a process shared by dancers and physically active individuals, and thus is less sensitive to domain-specific training effects. Consistent with these differences, we expect greater behavioral accuracy in dancers, but similar reaction times between groups, suggesting an advantage in cognitive efficiency rather than executive speed. This pattern would suggest a better balance between speed and accuracy in the dancers, mediated by a more effective proactive cognitive control system.

Regarding reactive (post-stimulus) processes, we expect to confirm previous ERP studies, finding in dancers lower P1 and larger P3 than in non-dancers, at least that one of these effects was driven

by the amount of physical activity and not the dance expertise. Regarding the other components, we hypothesize an increase in pN1 in dancers, indicative of increased sensory awareness and early top-down monitoring of input, especially in contexts that require rapid discrimination and attentional control (e.g., Perri et al., 2014). For N1, we expect to find no differences between groups, since it represents a basic visual and attentional processing stage that is also potentially common to physically active but non-dancing subjects. We also expected an increased amplitude of the pP1 component in dancers, which is associated with sensorimotor integration and rapid motor planning in tasks with high attentional demands (e.g., Di Russo et al., 2019). As these features are peculiar to dance (Bläsing et al., 2012) compared to other types of physical activity, we hypothesize this result would reflect greater synchronizing between perception and action, consistent with choreographic training. We also expect a reduced pP2 amplitude due to the less need for post-perceptual control processes. As pP2 is linked to stimulus-response mapping processing of sensory evidence accumulation when decision-making is required (e.g., Gonçalves et al., 2018), efficient perceptual filtering could allow for a reduction in the accumulation of sensory stimuli in stimulus-response evaluation and mapping processes, in line with faster and more automated stimulus categorization.

This results pattern would support the hypothesis that choreographic training induces specific neurophysiological adaptations related to the dynamic integration between attention, perception, and action, and not simply due to the amount of exercise.

Materials and Methods

Participants

The sample size was calculated using G*power 3.1.9.7 software (Faul et al., 2009) using Cohen's statistics and setting the following parameters for a two-tailed t-test for an independent samples design: a medium effect size d_z of 0.5, an intended power of 0.78, and a level of 0.05. This yielded a sample size of 32. Therefore, 16 professional dancers (mean age 22.9 years, $SD=2.6$, 88% females) were recruited. These dancers were all active members of the Molinari Art Center of Rome, all attending, for at least one year, a weekly training program of dancing (5 days per week, 4.5 hours of training per day). As controls, a group of 16 age and sex-matched individuals (mean age 22.3 years, $SD=1.7$, 88% females) was also recruited. As inclusion criteria, they were required to have performed in the last 6 months physical activity at least 3 days per week and at least 2

hours per day. The controls practiced various sports such as soccer, volleyball, clay shooting, and tennis, but none of them had ever practiced dance.

In both groups, the level of physical activity was assessed using the International Physical Activity Questionnaire Short Form (IPAQ-SF). Preliminary t-tests revealed no differences between the groups ($t < 1$) concerning age, education, and physical activity. Both groups fulfilled the IPAQ-SF criterion for “Very Active”. None of the participants had a history of cardiovascular or neurological conditions, nor were they currently taking any medications that may impair cognitive performance. In accordance with the Declaration of Helsinki, each participant gave their informed consent before participating in the study, which was authorized by the local ethics council at the University of Rome.

Procedure

Participants executed a visuomotor DRT (Go/No-go type) during EEG recordings. Participants were tested in a semi-dark, soundproof room after the EEG cap was applied to their scalps. Participants sat in front of a computer screen 114 cm away from their eyes and used their right index finger to tap a response box. As shown in Figure 1, a fixation point appeared on a black background in the center of the screen at the beginning of each run and stayed there the entire run. Four visual stimuli were randomly and individually displayed for 250 ms each. Each had an equal probability ($p=0.25$) and was represented by a square arrangement of $4 \times 4^\circ$ bars that were either vertical or horizontal ones. To avoid anticipation and ERP overlaps with the previous or next stimulus, the intervals between stimulus onsets were spaced 1500-2000 ms apart. Two predefined target stimuli ($p=0.5$) were shown to the individuals, who were told to click the button as soon as they appeared. It was forbidden to react to non-target stimuli ($p=0.5$). The instructions placed equal emphasis on speed and accuracy. The stimuli were not delivered in a predetermined order. Short breaks were allowed between runs. Over 25–30 minutes, ten runs were carried out, resulting in 400 trials for each stimulus category.

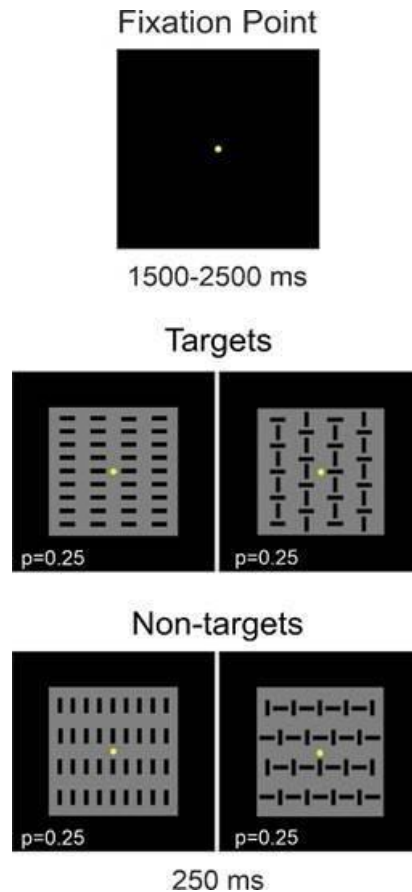


Figure 1. Representation and timing of the stimuli used in the DRT, with the distinction made between target and non-target stimuli.

Behavioral data

Response speed was obtained by measuring the mean response time (RT) for target trials. Accuracy was assessed by calculating the error rate, which was derived from the sum of the missed responses (i.e., omitted responses to target stimuli) and false alarms (i.e., responses to non-target stimuli).

EEG data recording and analysis

Three BrainAmp™ 32-channel amplifiers were used, two of which were linked to ActiCap's 64 active scalp sensors, and the other (ExG type), was used for bipolar electrooculogram (EOG). The Recorder 1.2 and the Analyzer 2.3 software were used to record continuous electroencephalogram (EEG) during the DRT and to analyze the data, respectively (all from BrainProducts GmbH, Gilching, Germany).

Scalp electrodes were mounted according to the 10-10 International System and were referenced to the average of M1-M2 electrodes. A Butterworth zero-phase filter (0.01–80 Hz; second order) was used as a band-pass, and a 50 Hz notch filter was applied. EEG was digitized at 250 Hz and saved for offline analysis. Eye movements were monitored using bipolar electrodes positioned above the outer canthi of the right and left eyes to record the horizontal EOG, and beneath and above the left eye to record the vertical EOG. The impedances of the electrodes were kept below 5 K Ω . The blink and vertical eye movement artifacts were automatically removed using the Analyzer's independent component analysis tool. After that, the data were automatically subjected to artifact rejection, which resulted in the removal of EEG signals with amplitudes higher than ± 70 μ V.

Both pre- and post-stimulus ERPs were calculated. For pre-stimulus ERP, the EEG was segmented into 1300 ms epochs, beginning 1100 ms before the stimulus presentation and concluding 200 ms following it. The first 200 ms (–1100/–900 ms) were used as a baseline. Target and non-target trials were averaged since the stimulus category was unpredictable during the pre-stimulus phase. For post-stimulus ERP, the EEG was segmented into 1200 ms epochs, beginning 200 ms before the stimulus onset and concluding 1000 ms following it. The initial 200 ms (–200/0 ms) were utilized as a baseline. Target and non-target trials were averaged independently.

Using the "collapsed localizer" approach (Luck & Gaspelin, 2017), which requires averaging the ERP of all groups and circumstances to generate a localizer ERP, intervals and electrodes for statistical analysis were determined a-priori. The analysis interval was determined by computing the global field power (GFP) on the localizer since the GFP analyzes ERP spatial variability across all scalp electrodes simultaneously.

For the pre-stimulus interval (Figure 2a), the GFP that at the t-test against zero resulted in a $p < 0.05$ was chosen, resulting in an interval between –316 and 0 ms. Electrodes that in this interval displayed an amplitude that at the t-test against zero resulted in a $p < 0.05$ were averaged in spatial pools. Two foci of activity were identified using this method: a medial prefrontal pool including Fp1, Fpz, and Fp2 representing the pN component and a medial central pool comprising the C1, Cz, C2, CP1, CPz, and CP2 electrodes representative of the BP components.

For post-stimulus ERP (Figure 2b), the GFP was also utilized to identify the components to be examined, choosing every peak that was present with a t-test against zero that corresponded to a

$p > 0.05$. For each peak, the time range in which the GFP t-test against zero resulted in a $p > 0.05$ was included to choose the interval surrounding the peak. Similarly, electrodes that showed in the selected interval amplitudes that at the t-test against zero resulted in a $p > 0.05$ were averaged into spatial pools. This method identified three intervals, the earliest from 100 ms to 132 ms, showing the bilateral parieto-occipital scalp topography of the P1 component that was represented by a pool including P7, PO7, P8, and PO8 electrodes. In the same interval, the medial prefrontal distribution of the pN1 component was also present and was exemplified by a pool including Fp1, Fpz, Fp2, AF3, AFz, and AF4 electrodes. The second identified interval ranged from 180 ms to 204 ms, showing the bilateral parieto-occipital scalp topography of the N1 component that was represented by a pool including the same electrodes used for the P1 component. In the same interval, the medial prefrontal distribution of the pP1 component was also present and was exemplified by the same pool used for the pN1. The third identified interval ranged from 448 ms to 558 ms, showing the medial centroparietal scalp topography of the P3 component that was represented by a pool including the C1, Cz, C2, CP1, CPz, and CP2 electrodes.

As done previously (e.g., Di Russo et al., 2019), to identify the pP2 component, the same analyses were applied to the differential ERPs obtained by subtracting in each participant the ERP obtained in response to non-target trials from that obtained to target trials. Using the same localizer procedure (Figure 2c), the pP2 was identified in the interval from 284 ms to 352 ms and visualized using a spatial pool including Fp1, Fpz, Fp2, AF3, AFz, and AF4 electrodes.

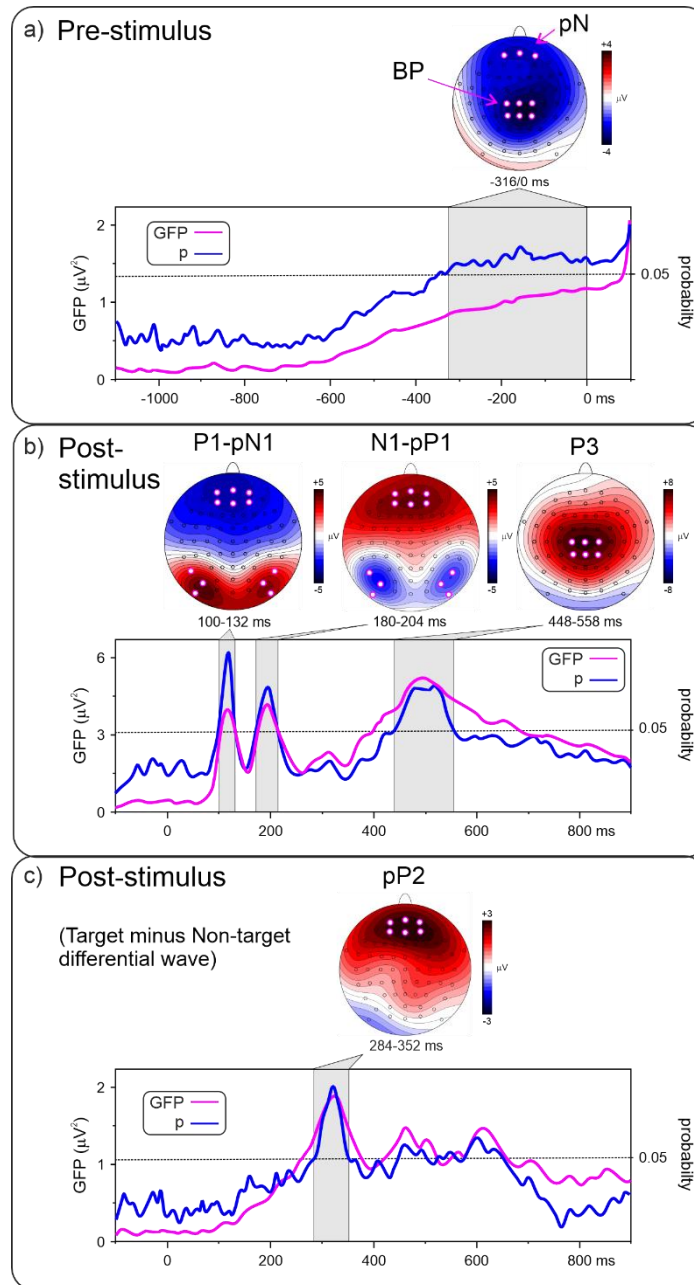


Figure 2: Global field power (GFP) of the collapsed localizers ERP (magenta lines), and the intervals selected based on the t-test against zero (blue line corresponding to the p value). a) Pre-stimulus interval, b) post-stimulus interval, c) Target minus non-target differential wave. The scalp topographies are relative to the indicated intervals, which are highlighted by grey shadows. The selected electrode pool is highlighted with white circles.

Statistical Analysis

Two-tailed t-tests for independent samples were used to compare the two groups regarding RT, accuracy, the pre-stimulus components (pN and BP), and the post-stimulus pP2 component amplitudes. Concerning the post-stimulus components P1, N1, pN1, pP1, and P3, amplitude was submitted to mixed 2×2 ANOVAs with Group (Dancers vs. Controls) and Trial (Target vs. Non-target trials) as between and within factors, respectively. The partial eta squared (η^2) was calculated to report effect sizes. For post-hoc comparisons, we applied Bonferroni correction. We assessed for each measure the assumption of normality using the Shapiro-Wilk's W test. The outcomes demonstrated that every measure followed normal distributions since they were all non-significant. The homoscedasticity assumption was evaluated using Levene's test for equality of variance, and no homoscedasticity violation was revealed. The overall alpha level was fixed at 0.05. The statistical analyses were conducted using Statsoft Statistica (StatSoft, Inc., Tulsa, OH, USA, version 12).

Results

Behavioral results

The t-test on the response time (RT), as depicted in Figure 3, showed a non-significant effect ($t < 1$), with a mean RT of 464 ms (SD=31) for the Dancers group and 460 ms (SD=26) for the Control group. The t-test on accuracy indicated a significant effect ($t(30) = -3.00$, $p = 0.01$) with a smaller error rate in Dancers (9.8%, SD=4.2) than in Controls (14.5%, SD=4.6).

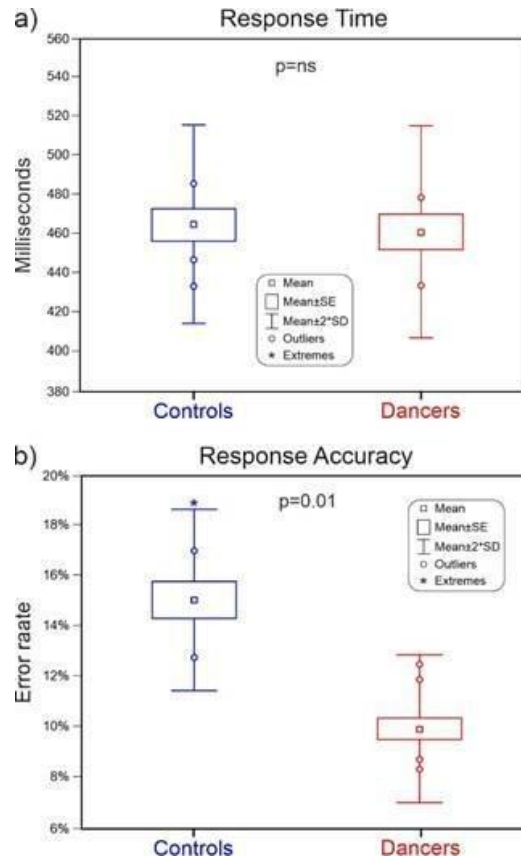


Figure 3. Behavioral outcome of the two groups in the visuomotor cognitive test. a) Response time, b) Response accuracy. The p-value (p) is also reported.

ERP Data

Figure 4 shows the pre-stimulus ERP waveforms of the two groups. The activity initiated about 800 ms before the stimulus onset, and the negativity slowly increased up to the stimulus onset. As shown in Figure 2a, the pN was characterized by a medial focus over prefrontal areas, and the BP by a medial focus over centroparietal areas.

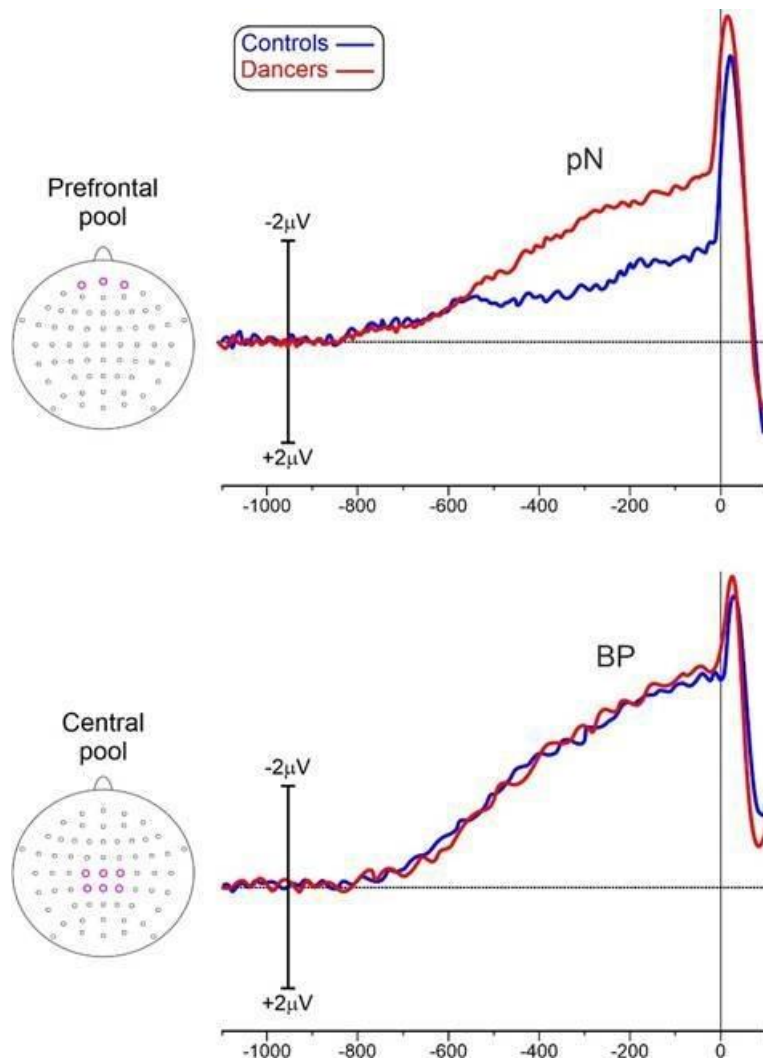


Figure 4. Pre-stimulus ERP waveforms comparing dancers (red line) and controls (blue line). ERP components are labeled. Purple circles in the head representation indicate the prefrontal and central electrodes included in the waveforms.

The t-test, as reported in Figure 5, made on the mean amplitude in the -316 to 0 ms interval was significant ($t(30)=-5.79$, $p<0.01$) for the prefrontal pool (pN component) showing higher amplitudes in the Dancers (-2.86 mV, $SD=0.78$) than Controls (-1.40 mV, $SD=0.63$). Differently, the t-test on the centroparietal pool (BP component) was not significant ($t<1$), being -3.84 mV ($SD=0.57$) in the Dancer group and -3.76 mV ($SD=0.98$) in the Control group.

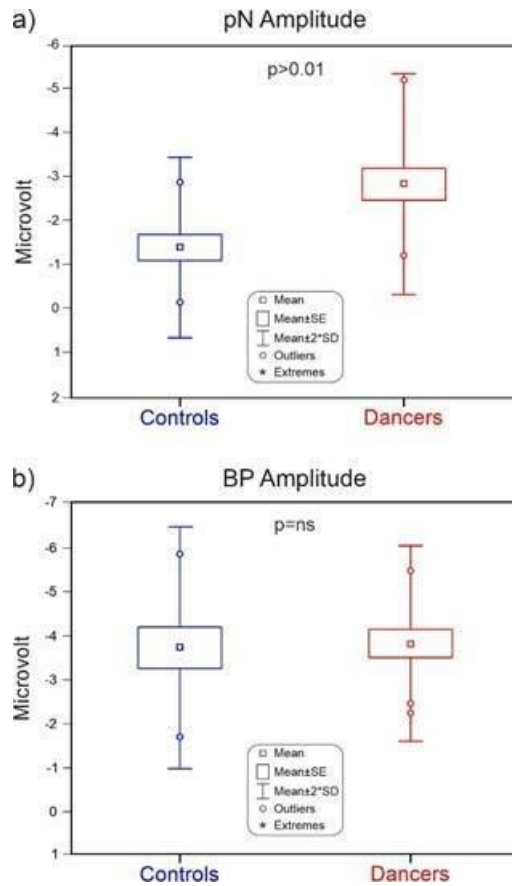


Figure 5. Group comparison of pre-stimulus a) pN and b) BP ERP component amplitudes. The p-value (p) is also reported.

Concerning the post-stimulus ERP components, the waveforms for the two groups are displayed in Figure 6. Near their peaks, the components under study (P1, pN1, N1, pP1, and P3) are labeled.

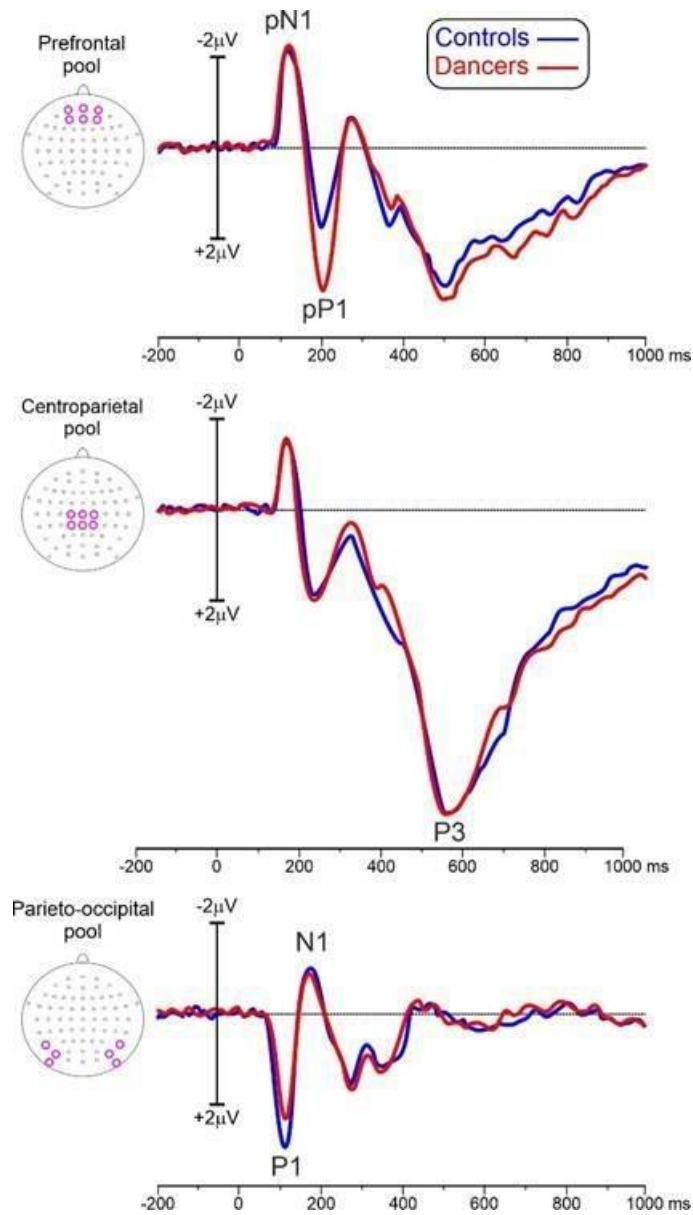


Figure 6. Grand-average ERP waveforms recorded during the DRT, comparing dancers (red line) and controls (blue line). ERP components are labeled at their respective peak latencies. Data are presented for three electrode pools: a) Prefrontal, b) Centroparietal, c) Parieto-occipital, indicated with purple circles in the head representation.

The ANOVA on the P1 components (**Figure 7a**) showed a significant effect of the Group ($F(1,30)=5.78$, $p=0.02$, $\eta^2=0.1615$ with smaller amplitudes in Dancers ($2.14 \mu\text{V}$, $SD=0.24$) than Controls ($2.62 \mu\text{V}$, $SD=0.27$), The Trial factor and the interaction were not significant ($F<1$).

The ANOVAs on the pN1 and N1 components revealed no significant effects and interactions ($F<1$).

ANOVAs on the pP1 (**Figure 7b**) showed a significant effect of the Group ($F(1,30)=39.38$, $p<0.01$, $\eta^2=0.576$) with larger amplitudes in Dancers ($3.32 \mu\text{V}$, $SD=1.32$) than Controls ($1.50 \mu\text{V}$, $SD=1.04$), The Trial factor ($F(1,30)=3.05$, $p=0.09$ and the interaction ($F(1,30)=1.49$, $p=0.23$) were not significant.

The ANOVA on the P3 (**Figure 7c-d**) showed a significant effect of the Trial ($F(1,30)=67.95$, $p<0.01$, $\eta^2=0.693$) with larger amplitudes for the target ($6.81 \mu\text{V}$, $SD=2.11$) than non-target ($5.81 \mu\text{V}$, $SD=2.05$) trials. The effect of the Group and the interaction were not significant ($F<1$).

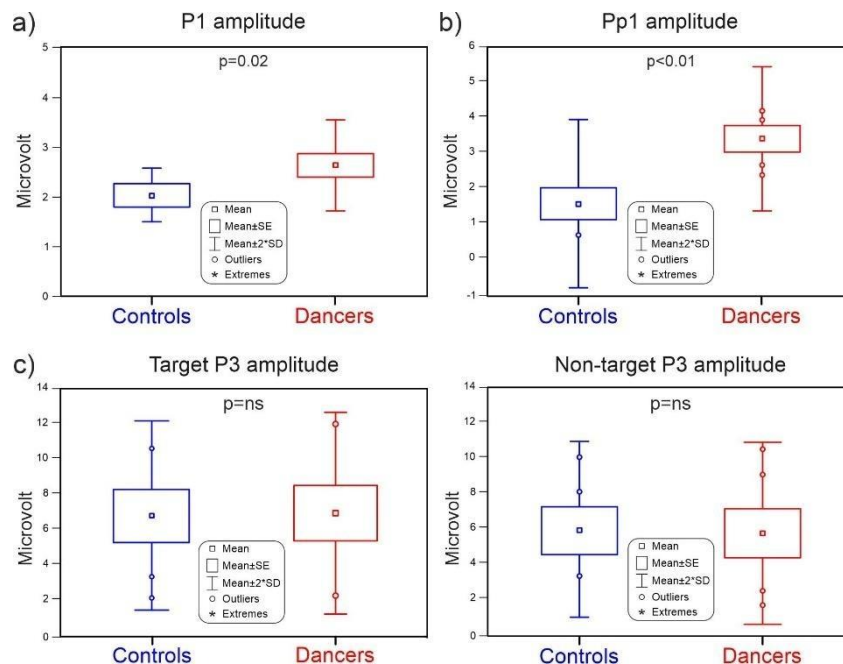


Figure 7. Group comparison of post-stimulus a) P1, b) pP1, and c) P3 ERP components. The p-value (p) is also reported.

Figure 8a shows the waveform of the pP2 obtained from the target minus non-target difference wave and peaking at 300 ms over prefrontal medial areas (Figure 2c). Figure 8b shows the t-test analysis on the pP2 amplitude reporting a significant Group effect ($t(30)=4.55$, $p<0.01$) with lower amplitude for the Dancers ($2.04 \mu\text{V}$, $\text{SD}=1.05$) than the Controls ($4.59 \mu\text{V}$, $\text{SD}=1.97$) group.

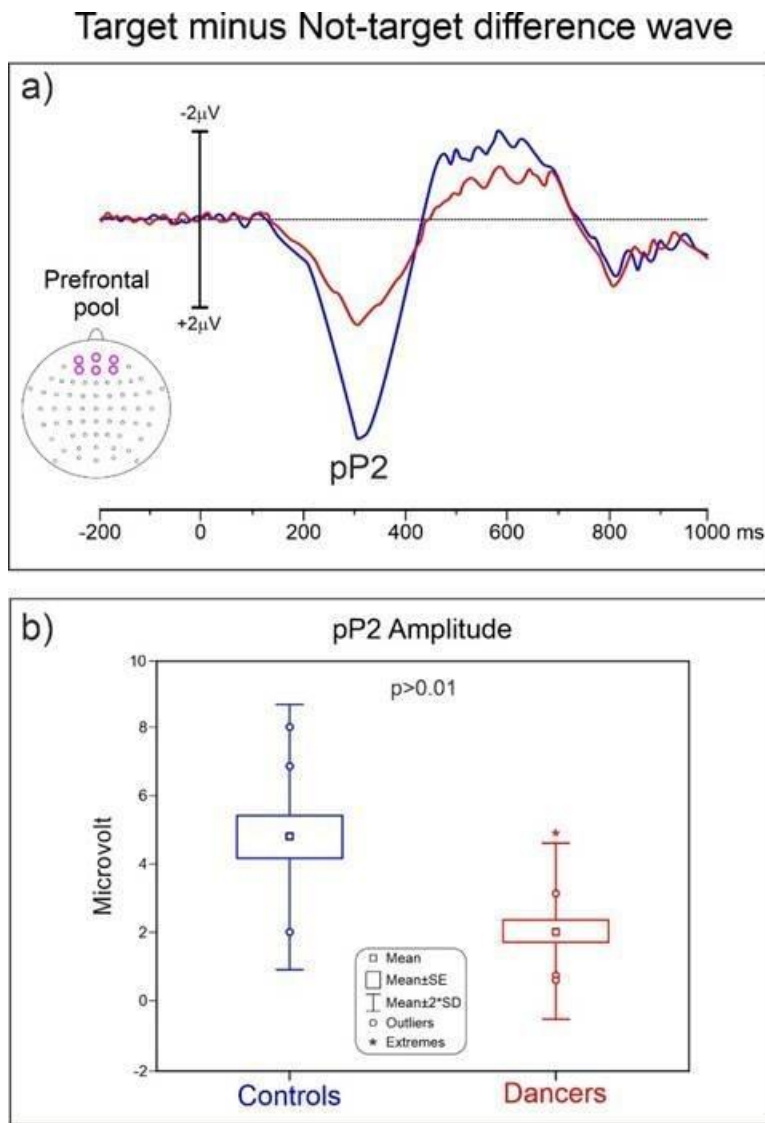


Figure 8. a) Grand-average ERP waveforms (target minus non-target) recorded from the prefrontal pool b) Group comparison the pP2 ERP components. The p-value (p) is also reported.

Discussion

This study aimed to investigate the neurophysiological adaptations of professional dancers to their intensive training identifying distinctive neural indices associated with their specific expertise. Dancers were compared with non-dancers, matched for physical activity level, in a cognitive task. Both pre-stimulus and post-stimulus ERP components associated with the task were studied, integrating them with behavioral performance.

Behaviorally, the two groups showed no response time differences in the task. This could be attributed to the comparable physical activity level, since literature consistently showed that response speed in cognitive tests could be affected by the amount of physical activity (e.g., Chueh et al., 2017; Nakamoto & Mori, 2008). In contrast, the dancers committed fewer errors in the task, suggesting higher cognitive control than non-dancers.

ERP data may explain the dancers' behavior in the cognitive task. The lack of difference in response time was paralleled by comparable BP amplitude in the two groups since that amplitude has been correlated with response time (e.g., Di Russo et al., 2019; Di Bello et al., 2024; Di Russo et al., 2006). This result suggests that mechanisms related to motor preparation, indicative of the excitability of premotor areas in preparation for action, are not affected by the intrinsic characteristics of choreographic practice. This is likely because the BP is considered an index of the motor readiness to perform a voluntary response and can be modulated by factors such as the intensity of motor training, familiarity with the task, and the complexity of the motor act required (Shibasaki & Hallett, 2006; Di Russo et al., 2019). The BP result is also in agreement with the IPAQ data, showing similar levels of physical activity in the two groups. The improved response accuracy found in the dancer group could be attributed to the pN component modulation, whose amplitude was much wider than controls. This finding is consistent with the hypothesis that the greater proactive cognitive control of dancers is mediated by more pronounced prefrontal activity during the preparatory phase of the task. The pN is associated with high-level cognitive processes, such as anticipatory attentional orientation, inhibitory regulation, and preparation for stimulus discrimination (e.g., Di Russo et al., 2017). Specifically, previous studies have shown that greater pN amplitude is related to more effective top-down attentional resource allocation, particularly in tasks that require rapid stimulus selection and inhibitory response to irrelevant targets (e.g., Berchicci et al., 2012; Perri et al., 2014). In the case of dancers, the reported pN increase could

reflect functional adaptation to a motor context in which anticipation, selection, and inhibition of responses are continuously exercised (Isoglu-Alkac et al., 2018; Blasing et al., 2012; Gldenpenning et al., 2012).

The ability to anticipate upcoming stimuli may have enabled dancers to make fewer errors than controls. Indeed, the ability to anticipate complex temporal and spatial patterns and to adapt action in real time according to choreographic or musical flow requires early and strategic involvement of those specific cognitive functions that reside precisely at the level of the prefrontal cortex (Blasing et al., 2012). Such activation would optimize subsequent decision making and minimize computational load in the post-stimulus phase, as also suggested by the observed decrease in the P1 and pP2. The finding is thus consistent with the interpretation of a particularly trained proactive cognitive control system in professional dancers. In fact, according to Calvo-Merino et al. (2010), skilled dancers are better at predicting their partners' movements, which is also connected to their ability to predict the outcomes of their actions. Additionally, improvisations are linked to timing and movement anticipation skills, and more frequent and appropriate movement is produced by seasoned dancers (Issartel et al., 2017). Due to improved time perception, their movements are perfectly accurate (Blasing et al., 2009).

Regarding reactive ERPs, as previously found, the P1 decrease might reflect suppression of low-level sensory input to reduce interference with endogenous tasks (Isoglu-Alkac 2018). The reduction of the pP2 component in dancers would suggest greater efficiency in the post-perceptual evaluation phase of the task. The pP2 has been associated with processes of conflict monitoring and stimulus-response mapping evaluation (e.g., Perri et al., 2015; Di Russo et al., 2019). Present results suggest that dancers, through prolonged exposure to tasks with high selective and coordination demands, develop more economical neural strategies in response management, reducing the need for massive involvement of prefrontal resources in decision-making (Isoglu-Alkac et al., 2018). Decreased pP2 would reflect less ambiguity in selecting the correct action or less cognitive load in solving the task, elements compatible with greater automation of response strategies. Indeed, some studies have shown that professional dancers routinely encode complex movement sequences through integrated systems that combine motor, spatial, and kinesthetic codes (Blasing et al., 2009; Cortese & Rossi-Arnaud, 2010; Kirsh et al., 2009). This type of encoding would facilitate not only recall but also rapid sensorimotor integration, supporting more efficient stimulus-response mapping.

The pP1 component was increased in the dancers' group, and this is consistent with the hypothesis of increased sensory-motor integration processes. Indeed, pP1 is an early component that reflects neural activation related to the synchronization between sensory stimulus processing and motor response planning (e.g., Perri et al., 2018; Gonçalves et al., 2018). In dynamic contexts with high coordinative demands, such as dance, strengthening such connections between perception and action would become crucial for generating rapid, accurate, and adaptive movements. In this regard, Bläsing et al. (2012) point out that neurocognitive control in dance involves highly specialized action-perception coupling processes, which develop through intensive choreographic practice and enable the dancer to anticipate, plan, and regulate movement as a function of rhythmic, visual, and spatial cues.

Finally, confirming the relevance of the dancers' sense-perceptual system, the P3 component, classically associated with decision-making and stimulus evaluation processes, showed no significant differences between dancers and controls. The lack of effect on P3 could be interpreted together with the earlier effect (pN and pP1), which would make it unnecessary to recruit more resources in the later stages. Dancers could complete the decision process more precisely, without having to intensify neural activity related to stimulus evaluation. Alternatively, the previously found P3 effect might have been due to differences in physical activity (e.g., Pedroso 2017).

Conclusion

In conclusion, the results emerging from this study seem to delineate a distinctive electrophysiological profile of professional dancers compared to generically active athletes, on both proactive and reactive brain activity. The marked difference observed in the anticipatory pN component suggests that dancers adopt a strong predictive cognitive control strategy, likely refined through years of exposure to complex choreographic tasks characterized by intense attentional demand and rapid response. Such an increase in pN could explain the concomitant reduction in reactive P1 and pP2 components, highlighting how more effective anticipatory preparation reduces the need for neural recruitment in later perceptual-decisional phases. In parallel, the increase in pP1 in dancers confirms the key role of sensorimotor integration in choreographic expertise. In this domain, the ability to transform visual, auditory, or proprioceptive sensory stimuli into smooth and synchronized motor actions represents a central competence, supported by specific neural processes already in the early post-stimulus phases.

Although these findings provide new evidence on the neurocognitive specialization of dancers, it must be emphasized that this area of research remains under-explored. Further investigation will therefore be needed, aimed at confirming these data and elucidating the mechanisms by which choreographic practice modulates brain activity in specific ways compared with other domains of motor expertise.

Meanwhile this study represents the first evidence of knowledge about the related neurophysiological aspects of dancers and their cognitive functions, it is necessary to acknowledge some methodological limitations that could affect the solidity of the inferences and suggest caution in interpreting the results. Indeed, the first limit to consider is the sample of the control group, which presents individuals with a high level of daily physical activity. However, the type of motor activity performed by the control group varied, so comparison with professional dancers may not be fair. Since we chose to include dancers from only one dance school to obtain participants with identical training, the number of participants is also a limitation of the study and does not allow for broad results generalizations to any category of dancers. So, as far as future studies are concerned, it would be necessary to compare the group of dancers with a group of participants practicing a specific sport, in order to obtain a more objective and equitable result. At the same time, broadening the sample size would allow a wider generalization of results.

4.5 Study 5: Effects of cognitive-motor training in virtual reality on anticipatory brain functions and balance of professional dancers

Abstract: This study investigated the effects of a virtual reality dual task cognitive-motor training protocol (VR-CMDT), based on the Creative Movement Hacking® methodology, on anticipatory neural correlates and balance in professional dancers. Twenty-four participants were divided in control groups, which followed standard training for 8 weeks, and experimental group that underwent the same training with an additional VR training session once a week. Before and after the intervention, both groups performed a Go/No-Go task with EEG, ERP recording and the Star Excursion Balance Test (SEBT). The results showed that the experimental group significantly increased the amplitude of prefrontal negativity, indicative of improved attentional and inhibitory control, and markedly reduced behavioural errors, with no changes in reaction times. At the motor level, only the experimental group showed a significant improvement in the SEBT, reflecting greater postural stability. These data support the effectiveness of VR-CMDT in optimising anticipatory cognitive functions and dance motor skills, suggesting its integration into professional training routines.

Keywords: Virtual Reality, Dual Task Cognitive Motor Training, ERP, Cognition

Introduction

Dancing is a universal modality of human movement expression, characterized by the integration of motor and cognitive aspects (e.g., Bläsing et al., 2012). In professional dance, correct performance execution is defined in terms of movement technique, expressiveness, and creativity. Specifically, the term technique refers to the quality of individual motor gestures during performance (e.g., Rehfeld et al., 2018). Similarly, the dancer's expressiveness concerns the ability to transfer through the body the emotional aspect intrinsic to the choreography (e.g., Bläsing et al., 2012; McNeely et al., 2015). Consequently, movement creativity reflects the ability to switch between gestures by adapting individual movements to dynamic and changing situational demands (e.g., Kattenstroth et al., 2010). In this context, effective dance training is fundamental since cognitive and motor control have a pivotal role in ensuring fine and optimal motor gestures and defining the performance of professional dancers. This is the result of complex neurocognitive processes, which combine motor control, cognitive anticipation, attention, visuomotor imagination, time synchronization, and motor memory (e.g., Golomer et al., 1999; Bläsing et al., 2012). Although data on neuroplasticity induced by dance practice is still scarce (Karpati et al., 2015), a careful analysis of the cognitive anticipation skills of dancers seems to show a profound ability to read and anticipate rhythmic, spatial and choreographic changes, a proactive neurocognitive strategy that would prepare the sensorimotor system to respond with precision and timeliness, anticipating the action before it fully manifests itself (Bläsing et al., 2012).

From a motor point of view, several studies have documented that professional dancers possess excellent postural control skills and dynamic balance, which are crucial for performing complex movements on unstable surfaces or during rapid transitions between supports. For example, long-standing studies such as Golomer et al. (1997, 1999) have shown that, compared to non-dancers, dancers exhibit less body sway on a moving platform and reduced dependence on visual input, indicating superior vestibular and proprioceptive control. Consistently, more recent studies indicated that experienced dancers exhibit higher balancing skills, likely maintain effective synchronization between the center of mass and pressure, than less experienced or non-dancers. (e.g., Bruyneel, et al., 2010; Chatfield, et al., 2007; Lin et al., 2019). These adaptations are the result of professional dance training and could reflect the enhancement of cerebellar and fronto-parietal brain networks, which support automated and voluntary motor and cognitive control, essential to cope with the demands of choreographic practice. Neuroscientific research on the

neural correlates of dancers seems to highlight a specific neuroplastic specialization. In fact, considering the fundamental relevance in the dancer's training process of cognitive systems related to observation, some studies conducted with fMRI have delved into their neural substrate (Cross et al., 2006). The results showed significant activation of brain networks deputed to observation and simulation of action, such as the premotor cortex and inferior parietal lobule. The amount of neural activity appeared to be correlated with both the participants' degree of experience with the danced movements and their perceived competence in performing them. In a subsequent study, Cross et al. (2009) fMRI scanned a group of non-dancers before and after a 5-day training session during which the subjects observed and performed movements taken from a dance video game. Even in this case, training-induced brain activity involved the motor observation and simulation networks, particularly the premotor cortex and inferior parietal lobule. Further evidence comes from two studies by Calvo-Merino and colleagues (2005; 2006), who found, using fMRI, increased activity in the premotor cortex when experienced dancers observed movements belonging to familiar dance styles compared to new ones. More pronounced activation was also recorded when subjects had direct motor experience in performing the observed sequences, compared with visual exposure alone. In later research, Pilgramm et al. (2010) showed that ballroom dancers exhibited greater activation of the premotor cortex, compared with non-expert subjects, when observing videos depicting ballroom dance steps. In the context of EEG studies on dance observation, Orgs et al. (2008) analyzed event-related desynchronization (ERD) in a sample consisting of experienced dancers and non-experienced subjects during the viewing of danced and non-danced movements. ERD, measured as a change in power in the alpha and beta frequency bands, is considered an index of inhibition of sensorimotor cortex activity by the action-viewing system (Muthukumaraswamy et al., 2004). The results showed that dancers exhibited greater desynchronization when viewing danced movements than non-experts, indicating a more pronounced activation of the action-observation system. More recently, Amoruso et al. (2014) used EEG to measure event-related potentials (ERPs) in a sample consisting of experienced tango dancers, beginners, and subjects with no dance experience while watching videos containing correct or incorrectly performed tango steps. Anticipatory activity generated by frontal, parietal and occipital regions showed significant differences between groups and predicted subsequent activation in motor and temporal areas, suggesting that experience in dance modulates not only perceptual processes but also neural preparation for the observed movement. Moving further into

specifics, remarkably interesting results are those reported by Ono et al. (2013). The researchers investigated the role played by the frontal regions of the brain, specifically the fronto polar parietal cortex (FPC), in a cognitive-motor task based on dance using fNIRS. Although typical bell-shaped responses of oxyhemoglobin (ΔoxyHb) variation in the middle temporal region (MTG) were observed in all participants, the time course and direction of responses in the FPC showed significant interindividual variability. Indeed, analyses of the results indicated that a suppression of the hemodynamic response in the FPC is associated with a greater number of steps performed with temporal accuracy. Because of its peculiar characteristics, low density of cell bodies, high number of dendritic spines per neuron, and high density of spines, FPC has been considered a supramodal regulatory region, particularly in cases where it is necessary to integrate the outcomes of two or more distinct cognitive operations in order to achieve a higher-order behavioral goal (Ramnani & Owen, 2004). Several studies have reported that FPC plays a crucial role in predictive encoding (Summerfield et al., 2006; Koechlin, 2011) or prospective memory (Burgess et al., 2001), functioning to hold the intention of a future behavior until the right time for execution based on environmental feedback. This neurocognitive process, as pointed out by Bläsing et al., 2012 seems to distinguish the performance of the professional dancer. The dance-based cognitive-motor task used by Ono et al. (2013) undeniably required this prospective memory; subjects had to prepare the correct sequence of steps from the rhythmic and visual cues, hold them in mind for a few seconds until the visual cues flowed to the response area, and then send the appropriate motor command to position themselves on the correct arrow key. In line with these findings, long-standing EEG studies, such as Fink (2009; 2013), wanting to analyze the construct of creativity in dancers showed that the latter was associated with higher levels of alpha synchronization in frontal and frontocentral regions of the brain. Specifically, the authors showed that the greater the creative demands of choreographic practice the greater the frontal alpha synchronization. This finding is confirmed in several scientific papers that aimed to study the neural correlates underlying the cognitive process of creativity (Fink & Neubauer, 2006; Grabner et al., 2007). The authors specified, that the greatest alpha activity in frontal regions was achieved not so much in the stages of idea or behavior processing and production, but in the anticipatory stages of ideation. In this context, alpha synchronization can be interpreted as a functional correlate of top-down inhibition or control (Sauseng et al., 2005; Klimesch et al., 2007). According to this perspective, alpha synchronization could reflect a mechanism for inhibiting cognitive processes not directly relevant

to task performance, such as retrieving interfering information during the retention interval in a working memory task (Klimesch et al., 2007). Such synchronization is particularly significant in the presence of internal processing demands, such as when participants are asked to temporarily hold information in their minds before making a decision. In this area, Sauseng et al. (2005) reported a particularly interesting study: the authors observed increased alpha synchronization in prefrontal regions during active manipulation of information in working memory, interpreting this finding as an indication of top-down selective inhibition. In particular, it has been hypothesized that frontal alpha synchronization may protect processing in working memory within frontal executive areas from interfering cognitive processes as long as information processing is ongoing. Creative thinking undoubtedly involves high internal processing demands. Indeed, the alpha synchronization observed during creative thinking could reflect a state of enhanced concentration or activation of the neural networks involved (Knyazev et al., 2006; Knyazev, 2007). Similarly, the alpha synchronization recorded during creative processes could indicate that information processing in specific brain areas is less subject to interference by other cognitive processes irrelevant to the task if idea generation is active. In this light, while it is true that the scientific literature has, through recent and long-standing studies, highlighted the relevance of cognitive processes in dancers' performance, it is equally true that there is no cognitive and sport-specific training methodology to increase the above cognitive skills in dancers. Indeed, while numerous training modalities emerge for strictly technical and motor skills (e.g. review Senger et al., 2024), the same cannot be expressed in the cognitive side. Several research conducted by our research group on the topic of dual task cognitive motor training (CMDT) have shown numerous benefits in increasing the performance of professional athletes. These training protocols are based on the now proven scientific evidence that, in high-intensity sports, performance depends not only on physical ability but also on the speed and effectiveness of attentional, decision-making and executive processes (Lucia et al., 2023a). In fact, the authors showed that the integration of CMDTs into the sessions of elite athletes significantly increased responsiveness, decision-making accuracy, and attentional resilience under competitive pressure conditions (Lucia et al., 2023a,b). Moreover, such protocols appear to promote neurofunctional adaptations in prefrontal and motor areas, promoting more efficient allocation of attentional resources and better management of cognitive load in competition. Indeed, from research conducted on basketball players, such protocols promoted rapid increases in both cognitive and sport-specific motor skills (Lucia et al.,

2021). Nowadays, despite the proven relevance of CMDT protocols on sport performance they still seem to be underused due to certain limitations on the compatibility between sport-specific contextual factors and cognitive instrumentation seem to emerge. In this regard, Staiano et al. (2022), discussing the limited use of such protocols, highlighted the limitations imposed by the training environment. According to the authors, in specific open-skills sports, it is not always possible to implement cognitive training protocols that are both sufficiently intensive and specific to meet the needs of competitive athletes. Given this, no practical examples of dance-focused cognitive training have emerged. However, Ehmann et al. (2022), in the context of soccer, used the Multiple Object Tracking (360-MOT) device, which involves placing screens around the player to create an immersive environment. This tool is designed to enhance functions such as peripheral vision, divided attention, and decision-making speed. The experimental group subjected to this protocol showed significant improvements in perceptual and cognitive functions; however, these results were not robust enough to be effectively transferred to the real game situation. To bridge this methodological gap, a promising strategy is the implementation of virtual reality (VR)-based protocols. VR has distinctive properties that make it particularly suitable for training cognitive functions. Among these, the ability to generate immersive and fully controllable environments stands out, which can be faithfully reproduced and modified with precision, thus allowing the simulation of complex and variable game situations that are difficult to achieve through conventional training methods. (Faubert, 2013; Fadde & Zaichkowsky, 2018). This allows, for example, athletes to be immersed in realistic but adaptable performance contexts, aimed at stimulating the perceptual and decision-making processes that are essential in competitive sports performance (Romeas et al., 2016). Virtual reality also allows for the integration of dynamic stimuli with simultaneous cognitive and motor tasks, which have been shown to be effective in enhancing selective attention, sensory perception, response time readiness, and, consequently, decision-making efficiency (Neumann et al., 2018; Michalski et al., 2019). Supporting traditional training methods, the use of VR allows athletes to repeatedly face specific sports situations, providing a safe but mentally challenging environment in which to develop anticipatory skills, creativity, and problem-solving skills (Bideau et al., 2010). One promising training method for professional dancers based on CMDT and VR is the patented protocol Creative Movement Hacking (CMH®) training system (Gasparotti 2024), which integrates the execution of choreographic sequences within three-dimensional geometric solids. This is realized using solid

types and sizes, and soundtracks with progressive difficulty. This VR-CMDT dance training seems to increase dancing technique, expressiveness, and creativity in only five weeks (Gasparotti, 2024), even though scientific evidence is lacking. Considering the proven relevance of cognitive and motor aspects in dancers' performances (e.g., Kattenstroth et al., 2010; Bläsing et al., 2012), and the now effectiveness of CMDT even using VR (e.g., Casella et al., 2024), this research project proposes to investigate the influence of the VR-CMDT protocol CMH® using motor and cognitive tests and electroencephalography (EEG). ERPs have been successfully employed to track the timing of cognitive processes from task preparation to motor execution because of their exceptional temporal resolution. During task preparation before the onset of events associated with a cognitive task, two primary ERP components, prefrontal negativity (pN) and Bereitschaftspotential (BP), respectively, have been used to index the anticipatory cognitive and motor functions (for data on a large dataset, see Di Russo et al., 2019). According to Di Russo et al. (2019), the pN has been connected to proactive cognitive processes such as top-down attention and inhibition in the prefrontal cortex during complex tasks, as well as response accuracy. According to Shibasaki and Hallett (2006), the BP is a motor readiness potential that appears before any deliberate activity and reflects the excitability of the supplementary motor and cingulate areas. It has also been suggested that these elements make up the neurological underpinnings of a cognitive system for activation/inhibition (braking/accelerating), which affects the trade-off between speed and accuracy by forecasting and anticipating future events and actions (Di Russo et al., 2019). Based on the above, we anticipate that the CMH® protocol in virtual reality will have effects on cognitive anticipatory functions rather than solely on motor skills. We hypothesize an improvement in pN, in experimental group. Conversely, considering that the entire sample included in this research consists of professional athletes with a specific and consistent motor training routine, we do not anticipate a substantial enhancement in BP, because the protocol prioritizes the capacity for precise response control and selection over pure motor preparation, hence mitigating premature impulses. In terms of motor function, we expect that this possible increase in pN and the resulting improvement in behavioural accuracy will also be reflected in balance performance. Postural control does not depend solely on automatic vestibular and proprioceptive mechanisms but also requires cortical input to anticipate changes in space and stabilise motor responses. More efficient cognitive control, capable of reducing impulsivity and improving response selection, can translate into more stable management of postural oscillations

and improved performance on the Star Excursion Balance Test (SEBT). In summary, we hypothesise that CMH® can enhance anticipatory cognitive processes and, indirectly, improve balance skills in professional dancers, representing an integrated model of cognitive-motor training aimed at optimising artistic performance.

Materials and Methods

Participants

Using Cohen's f statistics, the G*power 3.1.9.2 software was used to determine the sample size. Based on a work with a comparable design and measures (Casella, 2024), we set the predicted effect size $f(V)$ for the current mixed 2×2 ANOVA design at 0.31. The α level was set at 0.05, and the intended power ($1-\beta$) was set at 0.95. These parameters estimated a sample size of 24. Accordingly, 24 professional dancers (two males, mean age 23.2 years ± 1.96) were recruited at the same professional dance school of Rome (the Molinari Art Center, The movement, Rome) to ensure a similar level of dance training and expertise. To assess the dancers' physical activity intensity, the International Physical Activity Questionnaire (IPAQ) was administered. Years of education were also noted. To be eligible for inclusion, participants must have completed at least five years of dance training, report no neurological, psychiatric, or medical conditions; no medication during the experimental session; normal or corrected-to-normal vision; and ignorance of the study's goal. Following the Declaration of Helsinki, each participant gave their informed consent before joining the study, which was authorized by the "Foro Italico" local ethics council at the University of Rome.

Procedure

Participants were pseudo-randomly assigned to two groups of 12: the experimental (Exp) and control (Ctr) groups. Groups were matched for sex. Preliminary t-tests were made to compare physical activity intensity, age, education, and expertise that did not differ between groups ($t < 1$). The IPAQ score (3.5 ± 0.3) classified both groups as very active.

For eight weeks, both groups attended the professional dance training program of the school, five days a week for six hours each day. Technical skills were the main focus of the training. In the second half of the daily program, the Exp group conducted for 30' the experimental training

described below. Just before and after the eight-week training. A motor and a cognitive test were administered to all participants. During the cognitive test, high-density EEG was also recorded.

Experimental training

The experimental training consisted of a virtual reality cognitive-motor dual-task (VR-CMDT) protocol, which was based on the Creative Movement Hacking® training method ideated by Gasparotti (2024). Participants, after wearing a VR headset (Oculus Meta Quest 3s), were placed inside a regular polyhedron and were asked to perform an improvisation dance for a predefined time (25-90”) as soon a music started (motor task). As a dual task, dancers were required to dance inside the polyhedron; otherwise, an error sound was emitted, associated with a red cross appearing on the touched areas of the polyhedron (cognitive task). The training presented eight levels of increasing difficulty that were defined by the combination of the following parameters: polyhedron type (cube, tetrahedron, octahedron, icosahedron, and dodecahedron) and size (large, medium, small), music tempo (40-180 bpm).

Motor Test

The Star Excursion Balance Test (SEBT) was used to assess the dynamic postural control and functional balance of the lower limbs (Gribble et al., 2012). The test consists of maintaining balance on one limb while the other performs a maximum extension in eight predefined directions, arranged radially in the shape of a star, thus assessing the individual's ability to stabilize the body during controlled, multi-directional movements. The scoring involves calculating the average reach distance in each direction (cm) and then normalizing it to a percentage of leg length. This task requires fine integration between proprioceptive, vestibular, and visual systems, and is therefore considered a sensitive indicator of neuromuscular function and motor control efficiency (Plisky et al., 2006).

Cognitive Test

A Go/No-go visuomotor discrimination response task (DRT) was conducted. The test was carried out in a soundproof, semi-dark chamber. Dancers maintained their right index finger on a response button while sitting 114 cm in front of a 32” computer monitor. As depicted in Fig. 1, Each trial began with a fixation point that stayed in the center of the screen against a black background for the duration of the run. For 250 ms each, four square configurations with vertical and/or horizontal

bars that extended $4 \times 4^\circ$ of the visual field were randomly shown. Each configuration had an equal chance ($p=0.25$). One to two seconds passed between stimulus onsets. The dancers were told to hit the button as soon as one of the target stimuli appeared; speed and accuracy were equally stressed. Two stimuli were designated as targets and two as non-targets. Non-target stimuli didn't demand a response. The stimulus order was random. Each run lasted roughly two minutes, with a 30-second break in between. Ten runs in all, or roughly 400 trials for each stimulus type, were carried out. The session lasted for around half an hour. The response time (RT) for targets expressed in milliseconds and the error rate (sum of missed targets and responses for non-targets) expressed in percentage were measured.

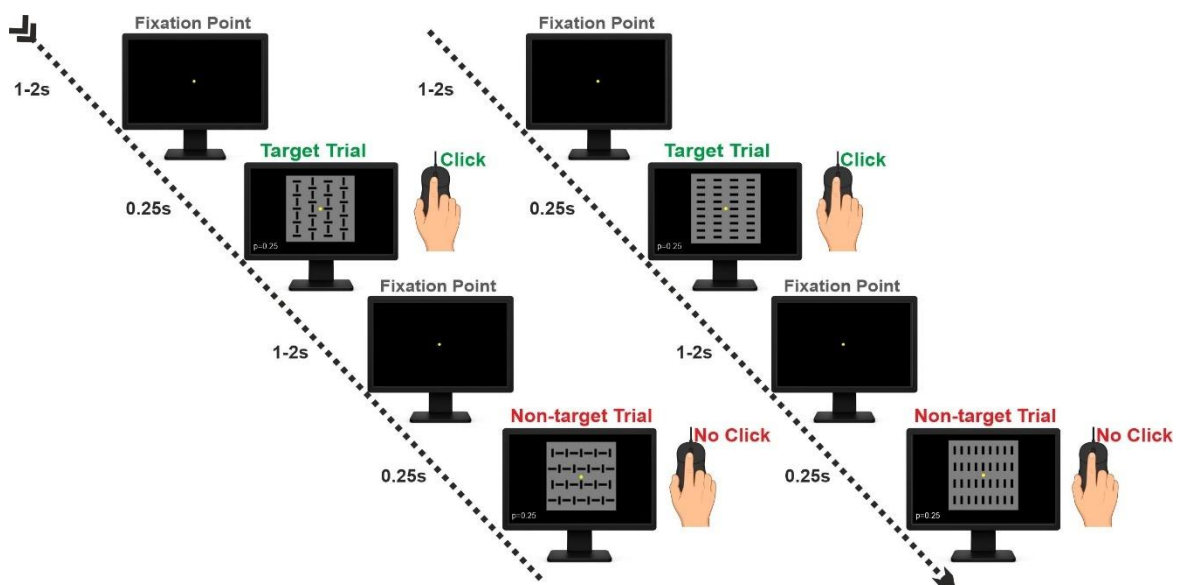


Figure 1: Schematic representation of the Go/No-Go task. After the fixation point (1–2 s), a stimulus was presented for 250 ms: in Target trials, participants had to respond with a click, while in Non-target trials, they were required to inhibit their response.

EEG Recording and ERP analysis

During the cognitive test, continuous electroencephalogram (EEG) was recorded using two BrainAmp™ amplifiers linked to ActiCap's 64 active sensors. The Recorder 1.2 and Analyzer 2.3 software were used (all by BrainProducts GmbH in Gilching, Germany). Electrode positions were based on the 10-10 International System and referred to the M1-M2 electrodes' average. A Butterworth zero phase filter (0.01–80 Hz; second order) was used to band-pass filter the digitalized EEG signals at 250 Hz before they were saved for offline analysis. The third BrainAmp

amplifier (ExG type), which monitored bipolar eye movements, was used to record the electrooculogram (EOG). Electrodes were positioned above and below the left eye to record the vertical EOG and over the outer canthi of the right and left eye to record the horizontal EOG. The impedances of the electrodes were kept below 5 K Ω . The blink and vertical eye movement artifacts were automatically examined using the Analyzer's independent component analysis tool. After that, the data were automatically subjected to artifact rejection, which resulted in the removal of EEG signals with amplitudes higher than the $\pm 70 \mu\text{V}$ threshold. EEG data were split into 1300 ms epochs, beginning 1100 ms before the stimulus presentation and concluding 200 ms later, in order to quantify pre-stimulus activity. The first 200 ms ($-1100/-900$ ms) were used as a baseline. Target and non-target trials were averaged because the stimulus categorization was unclear during the pre-stimulus period.

As shown in Fig. 2, the intervals and electrodes for statistical analysis were determined a-priori using the "collapsed localizer" approach (Luck & Gaspelin, 2017), which involved averaging the ERP of all groups and conditions to create a localizer ERP. The analysis interval was determined by computing the global field power (GFP) on individual ERP and then on the localizer. The GFP indicates the ERP spatial variability across all scalp electrodes simultaneously. The interval was selected by performing a t-test against zero on the GFP and taking the interval with significant values ($p < 0.05$) starting from time zero and going backward. In this manner, the mean amplitude between -304 and 0 ms was calculated for statistical analysis. The electrodes in the selected interval of the localizer that had a t-test against zero with $p < 0.05$ were included in a spatial pool, averaging them. Two pools of activity were identified using this method: a medial prefrontal pool (AF7, Fp1, Fpz, Fp2, AF8) representing the pN component and a medial centro-parietal pool comprising the (C1, Cz, C2, CP1, CPz, CP2 electrodes representing the BP component.

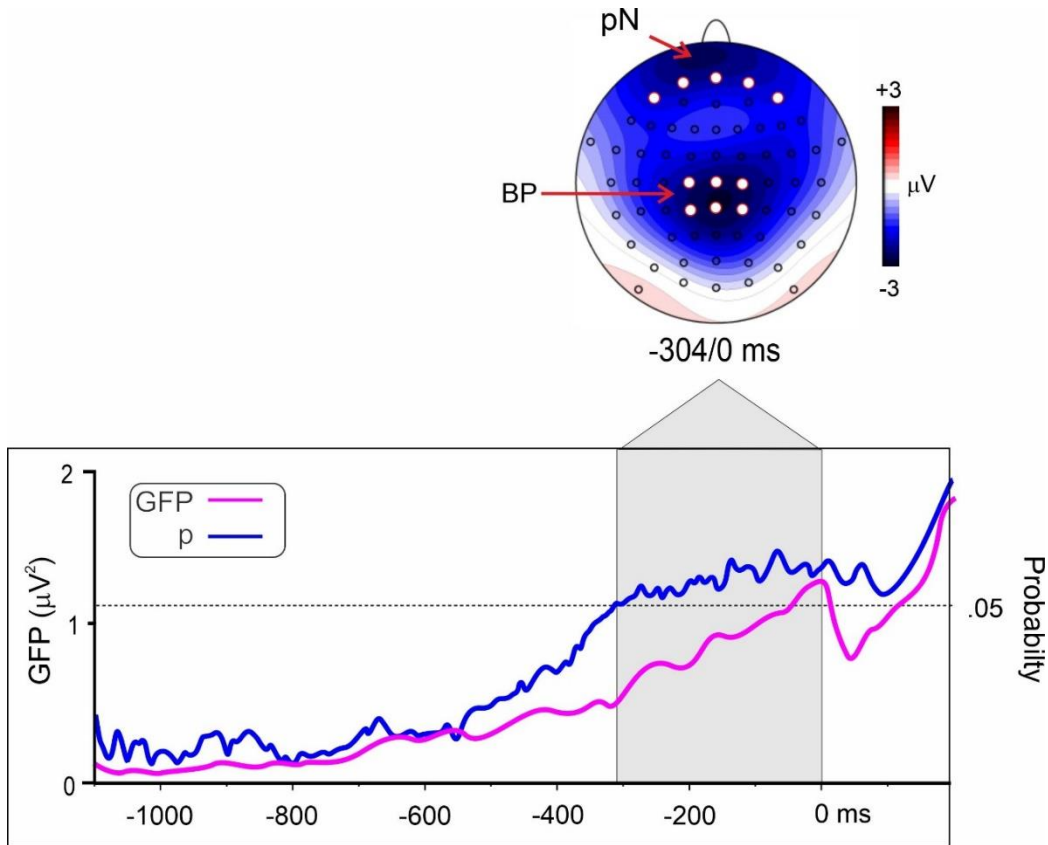


Fig 2: Global field power (GFP) of the collapsed localizers ERP (magenta lines), and the intervals selected based on the t-test against zero (blue line corresponding to the p value)

Statistical Analysis

The Shapiro-Wilk's W test was used to evaluate the assumption of normalcy for each metric. The results showed that all of the measures were non-significant, indicating that they all followed normal distributions. Using Levene's test for equality of variance, the homoscedasticity assumption was assessed, and no violations of the homoscedasticity assumption were found. All measurements were subjected to mixed 2X2 ANOVAs after these preliminary tests, with Time (T0 vs. T1) as the within factor and Group (Exp vs. Ctr) as the between factor. The squared partial eta (η^2) was computed as an estimate of the effect sizes. The Bonferroni correction was for post-hoc comparisons. The threshold for alpha was set at 0.05. Statistica 12.0 (StatSoft Inc., Tulsa, OK, USA) was used for statistical analyses.

Results

Motor Test

The ANOVA on the balance test (SEBT) showed a significant effect of Time ($F(1,22)=14.5$, $p<0.05$, $\eta^2=0.397$), with larger leg extension in T1 (61.1 cm \pm 9.6) than T0 (67.1 cm \pm 11.3). The Group factor was not significant ($F(1,22)=2.4$, $p=0.13$). The Time x Group interaction was significant ($F(1,22)=4.5$, $p<0.05$, $\eta^2=0.169$) and post-hoc comparisons showed that the Exp group had in T1 (70.3 cm \pm 10.4) larger leg extension ($p>0.01$) than T0 (61.0 cm \pm 5.9), in the Ctr group, the difference was not significant (T0= 61.2 \pm 5.7, T1=63.8 \pm 6.1). Fig. 3 shows this interaction.

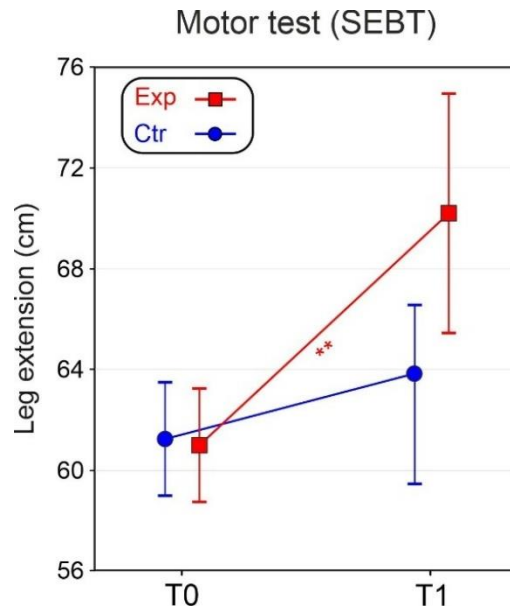


Fig 3. Interaction between Group and Time in the Star Excursion Balance Test (SEBT). The vertical line represents the 0.95 confidence interval. ** $p<0.01$.

Cognitive Test: Behavioral Results

ANOVA on the RT showed a significant main effect of Time ($F(1,22)=9.5$, $p<0.001$, $\eta^2=0.301$) with lower RT in T1 (501 ms \pm 48) than T0 (529 cm \pm 50). The Group effect was not significant ($F<1$). The Time x Group interaction was not significant ($F(1,22)=2.6$, $p=0.129$); however, post-hoc comparisons showed in the Ctr group a RT decrease ($p<0.05$, T0=531 ms \pm 58, T1=489 ms \pm 50). In the Exp group, the difference was not significant (T0=527 ms \pm 56, T1=514 ms \pm 51). Fig. 4a shows this interaction.

The ANOVA on the error rate showed a significant effect of Time ($F(1,22)=43.2$, $p<0.01$, $\eta^2=0.663$) with fewer errors in T1 ($1.8\% \pm 0.1$ than T0 ($5.5\% \pm 0.6$). The Group factor was not significant ($F(1,22)=1.1$, $p=0.31$). The Time x Group interaction was significant ($F(1,22)=6.4$, $p<0.05$, $\eta^2=0.226$) and post-hoc comparisons showed in the Exp group a decrease ($p<0.01$) in the error rate (T0= $5.9\% \pm 0.5$, T1= $0.8\% \pm 0.1$). In the Ctr group, the difference was not significant (T0= $5.2\% \pm 0.6$, T1= $2.9\% \pm 0.2$). Fig. 4b shows this interaction.

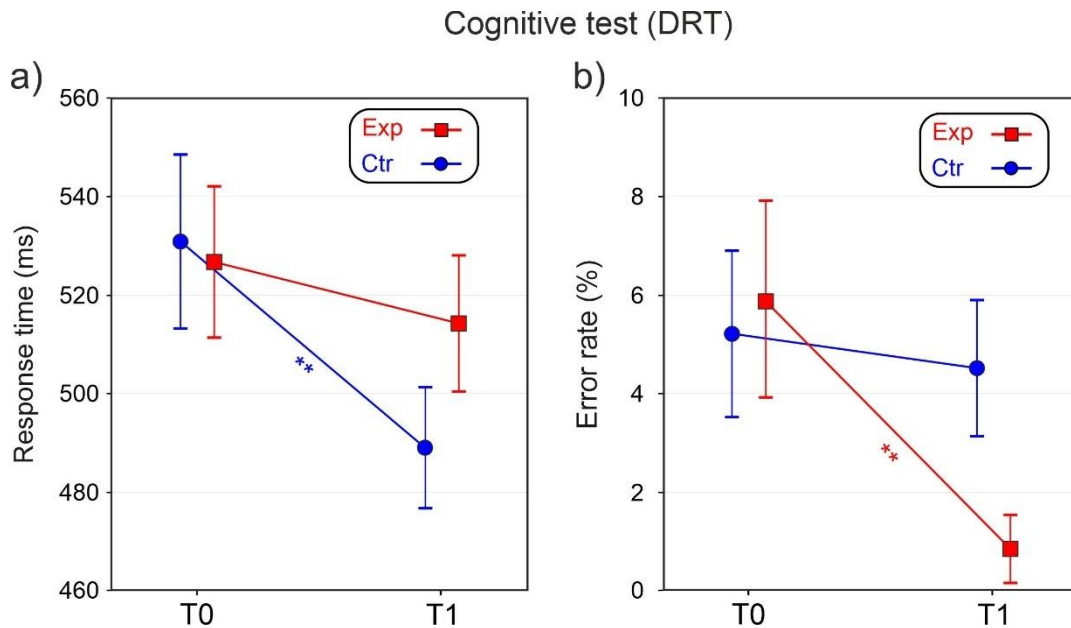


Fig 4. Interaction between Time and Group in the discrimination response task (DRT) cognitive test. a) Response time (RT), b) Accuracy (error rate). The vertical line represents the 0.95 confidence interval. ** $p<0.01$.

Cognitive Test: ERP Results

Fig. 5 shows the pre-stimulus ERP waveforms in the two Groups and conditions. The BP is detectable starting from -650 ms and emerging as a slow-rising negativity reaching its peak at stimulus onset on medial central sites. The pN initiated at about 500 ms and peaked at stimulus onset on medial prefrontal sites.

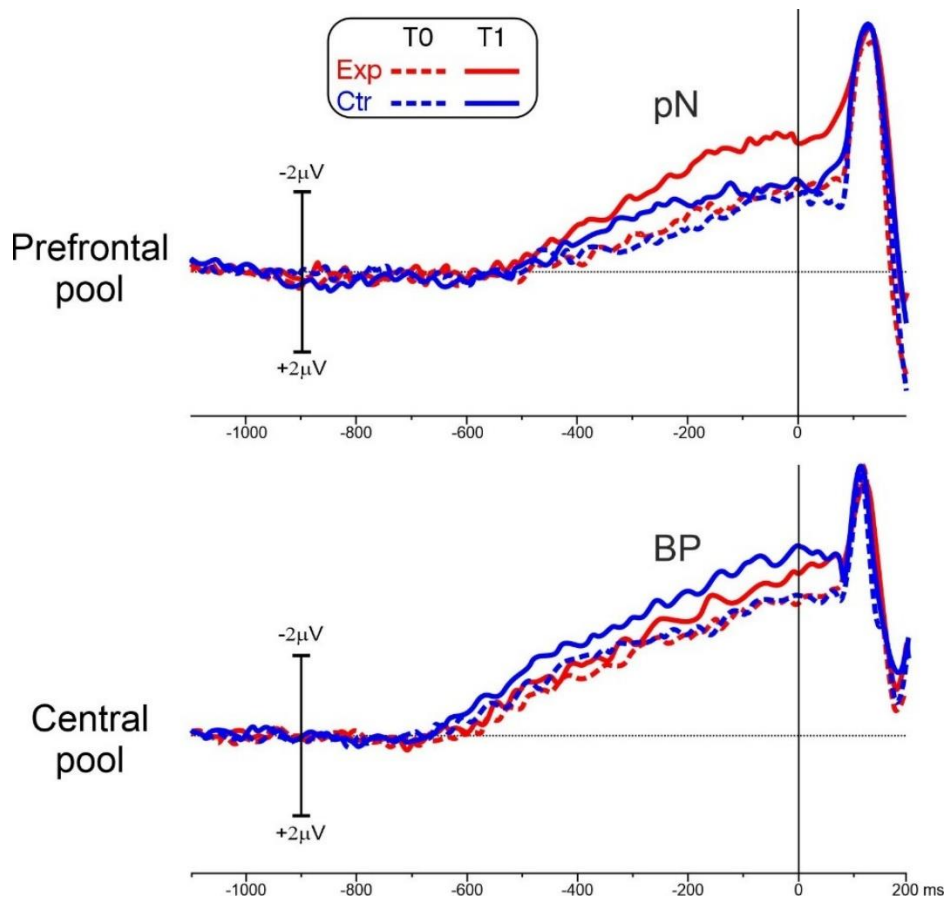


Figure 5. ERP waveform related to the cognitive task for the Experimental (Exp) and Control (Ctr) groups in T0 and T1. The upper and lower panels show the prefrontal and the central pools of electrodes marked in **Fig. 2** and representing the pN and the BP, respectively.

ANOVA on the BP showed a significant main effect of Time ($F(1,22)=7.0$, $p<0.05$, $\eta^2=0.242$) with larger amplitude in T1 ($2.64 \mu\text{V} \pm 0.97$) than T0 ($1.88 \mu\text{V} \pm 0.86$). The Group and the interaction effects were not significant ($F(1,22)<1$). However, post-hoc comparisons showed in the Ctr group an increase in BP ($p<0.05$, $T0=-1.88 \mu\text{V} \pm 0.82$, $T1=-2.74 \mu\text{V} \pm 0.75$). In the Exp group, the difference was not significant ($T0=-1.87 \mu\text{V} \pm 0.81$, $T1=-2.55 \mu\text{V} \pm 0.92$). This interaction is reported in **Fig. 6a**.

ANOVA on the pN showed non-significant effects of Time ($F(1,22)=1.84$, $p=0.18$) and Group ($F(1,22)=1.53$, $p=0.23$). However, the interaction was significant ($F(1,22)=8.7$, $p<0.01$, $\eta^2=0.285$) and post-hoc comparisons showed in the Exp group an increase in pN ($p<0.01$, $T0=-$

0.78 $\mu\text{V} \pm 0.44$, T1=-2.64 $\mu\text{V} \pm 0.98$). In the Ctr group, the difference was not significant (T0=-0.82 $\mu\text{V} \pm 0.49$, T1=-1.41 $\mu\text{V} \pm 0.84$). This interaction is reported in Fig. 6b.

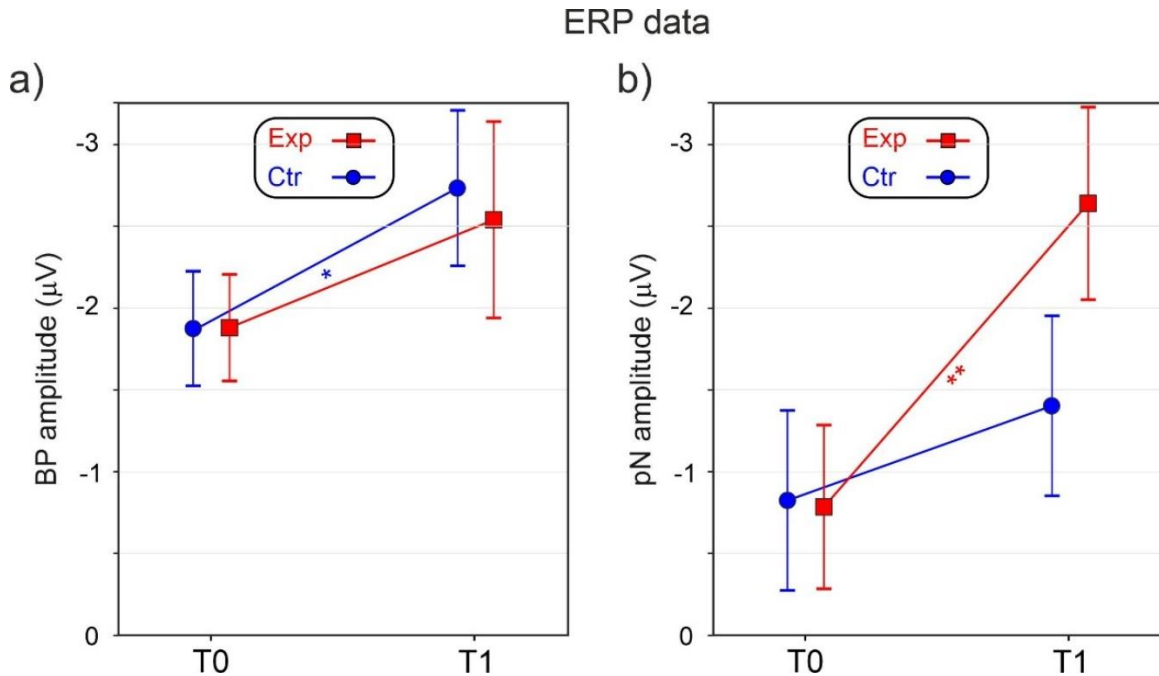


Fig. 6. Interaction between Time and Group of the ERP data. a) BP component b) pN component. The vertical line represents the 0.95 confidence interval. * $p < 0.05$, ** $p < 0.01$.

Discussion

Based on the evidence emerging from studies conducted on CMDT in sports (Casella et al., 2024; 2025; Lucia et al., 2021; 2023a; 2023b; 2024; e.g. review Wu et al., 2024), and considering the proposed experimental training nature, we hypothesised that the latter could simultaneously stimulate cognitive anticipation systems, particularly at prefrontal cortex level, and postural control systems, thus promoting an integrated improvement of the two components. The CMH® protocol, in fact, is characterised by the necessary integration between cognitive and motor skills: participants had to perform choreographic sequences within spatial and rhythmic constraints defined by virtual geometric solids, while maintaining attentional and inhibitory control to avoid execution errors. According to the hypotheses, the results showed that, at the electrophysiological level, the experimental group significantly increased in pN, index of top-down proactive control

and inhibitory processes, without significant changes in BP, traditionally linked to motor preparation. In contrast, post-hoc comparisons showed that the control group reported a slight increase in BP. Behaviourally, the dancers in the experimental group drastically reduced the number of errors in the Go/No-Go task while maintaining stable reaction times, while the control group, in line with the electrophysiological data, showed a reduction in reaction times without corresponding improvements in accuracy. Finally, at the motor level, only the experimental group reported a significant increase in performance in the SEBT.

Therefore, in agreement with Di Russo et al. (2017) and Standage et al. (2014), it appears that the VR-CMDT proposed here induced the so-called speed-accuracy trade-off (SAT) in athletes. In dynamic, changing and complex situations, such as sports performance, the ability to balance speed and accuracy is a fundamental characteristic of decision-making processes (Chittka et al., 2009; Bogacz et al., 2010a; Heitz & Schall, 2012). When the task is equally difficult, decisions tend to be quicker but less accurate when the context favours speed, while they are slower but more accurate when the goal is accuracy (Standage et al., 2014). In fact, the experimental group subjected to the CMDT-VR protocol for eight weeks showed a significant increase in pN, and accuracy compared to the control group. This result appears consistent with the nature of the experimental task, in which the cognitive skills of selective attention and inhibition were essential to perform the dance sequences in time with the musical bpm and avoid errors within the virtual geometric solids. The simultaneous presence of partly contrasting sensory stimuli — on the one hand, the limited space, and on the other, the progressive acceleration of the musical rhythm — probably led the participants in the experimental group to prioritise cognitive-motor accuracy over response speed, favouring more stable and less impulsive control, in line with the specific requirements of dance performance. From an electrophysiological point of view, it seems clear that this training practice has functionally modulated the entrainment of dancers (Large et al., 1999; Damm et al., 2020), i.e. the nervous system's ability to synchronise its internal activity with periodic external stimuli, adapting the frequency and phase of neural responses to the temporal and spatial constraints of the environment (Ross et al., 2014; Damm et al., 2020). Particularly interesting aspect is that emerges from the analysis of the electrophysiological and behavioural results of the control group concerns the well-known effect exerted by exposure to music and, more generally, by musical training in increasing the activity of the motor and premotor areas. (Damm et al., 2020; Kotz et al., 2018). In particular, the rhythmic structure of music, characterised

by temporal regularity and hierarchical organisation, naturally promotes the coupling between perception and action. (Kotz et al., 2018). The ability to extract temporal regularities and align motor responses to the periodic structure of rhythmic sequences, such as the metrical accent of music, is in fact an almost universal trait in human beings. (Honing, 2012). Neuroimaging and electrophysiology evidence has consistently demonstrated that rhythmic entrainment involves audio-motor networks, including premotor areas, the supplementary motor area, and the basal ganglia. (Chen et al., 2006; Thaut et al., 2009). It is important to emphasise that this motor activity does not necessarily require the actual execution of the movement: the mere perception of temporally structured stimuli is sufficient to activate the motor cortical regions. (Thaut et al., 2009). These data could well explain why both groups, with a slight significance in the control group at the expense of the experimental group, reported an increase in motor preparation and reaction time. In fact, the constant need to integrate auditory sensory aspects with motor aspects, produced by the weekly training routine, may have led to the increase shown in BP and RT in the athletes. Although ERP studies seem to be scarce in this area, some interesting connectivity research may explain the increase shown in BP. The latter have demonstrated how simply passively listening to sound stimuli modulates both the power and phase coherence of oscillations in the beta band in various cortical and subcortical areas, including the sensorimotor cortex, inferior frontal gyrus, motor area, supplementary motor area, and cerebellum. (Fujioka et al., 2012). These modulations would reflect the brain's preparatory and predictive processes in response to rhythmic auditory signals (Pranjic et al., 2024). In particular, the motor areas and especially the supplementary motor area (SMA) appear to be involved in covert beat generation, a fundamental process in dance practice, in which it is necessary to maintain an internal representation of the beat even in the absence of external stimuli. This mechanism could well explain the increase in BP observed in both groups of dancers, since dance practice, regardless of the type of training, requires the constant ability to maintain an internal sense of the musical rhythm and use it as a reference for motor preparation (Chauvignè et al., 2014; Witt et al., 2008; Jantzen et al., 2007; Rao et al., 1997; Mayville et al., 2002) In this sense, the increase in BP could reflect the activation of SMA linked to maintaining and synchronising the beat, an aspect shared by all the dancers involved in the study. It therefore seems that the dancer's nervous system has “learned” to use the auditory inputs produced by music as quickly and functionally as possible in response to the demands of performance. On the other hand, as previously reported, analysis of the results

showed a significant increase in pN in the experimental group. The marked increase in this component could be interpreted in light of the predominant role of the frontal and prefrontal areas in monitoring and organising behaviour. (McCloskey et al., 2013). It is well known that the frontal cortex performs supervisory, planning and control functions, and its activation is particularly stimulated in conditions that require the management of complex environmental constraints. . (Flock & Walla, 2020). In our protocol, virtual geometric solids represented a limited space within dancers were required to move, synchronising themselves with the progressive increase in musical rhythm. This context probably generated a condition of attentional pressure and potential perceptual ambiguity, in which selecting the correct response required constant top-down intervention from the prefrontal regions. In line with the literature, is possible that environmental limitations have triggered bottom-up processes linked to subcortical mechanisms such as the amygdala and its role in processing ambiguous or potentially threatening stimuli. (Suslow et al., 2006), and top-down processes, in which the prefrontal cortex exercises monitoring and inhibition control over automatic responses. A second, alternative and complementary interpretation involves the activity of the anterior cingulate cortex (ACC), which is frequently associated with increased attention and selectivity in tasks that require the management of contextual constraints. (Flock & Walla, 2020). In this context, the increased fronto-prefrontal activation measured by pN in the experimental group could reflect the need to direct attentional resources towards the relevant aspects of the task, i.e., compliance with the musical rhythm and spatial constraints, minimising the impact of distractions or sources of ambiguity generated by the virtual environment. The relevance of the data found in this study is further confirmed by recent research conducted by our group, aimed at identifying the neural correlates of professional dancers (Casella et al., 2025). That work revealed a specialisation of the dancers' nervous system at the pN level, whose greater amplitude was interpreted as a functional adaptation to a motor context in which anticipation, selection and inhibition of response are continuously exercised (Isoglu-Alkac et al., 2018; Bläsing et al., 2012). The fact that the CMDT-VR proposed here also led to a significant increase in this component, which from an anticipatory point of view proved to be particularly sensitive in discriminating dancers from other populations, further supports the practical implications of this protocol and suggests its usefulness as a tool to be integrated into professional training routines. Furthermore, this protocol, in line with research conducted on CMDT, (Lucia et al., 2021; 2023a; 2023b; 2024), has also been shown to produce benefits in terms of motor skills. In particular, in

this study, the experimental group reported a significant increase in performance as measured by the SEBT, highlighting an improvement in dynamic postural stability, a motor skill specific to dance that is fundamental for dancers. (Blasing et al., 2012). It is important to highlight that, as observed in the aforementioned studies on CMDT, both groups, consisting of athletes, reported benefits in sport-specific motor skills. However, the nature of CMDT, based on the simultaneous integration of cognitive and motor stimuli, allowed the experimental group to show greater motor gains than the controls, confirming the effectiveness of the proposed protocol in optimizing balance and postural control in highly complex contexts such as dance.

General Discussion

In recent years, open-skill sports have been increasingly interpreted as complex dynamic systems, with high environmental variability, unpredictable stimuli, and intense time pressure (Williams et al., 2019). Athletic performance must now be evaluated not only through physical or technical metrics but as a product of the ongoing interplay between perception, cognition, and action. The evolution of research methodologies – from advanced match analysis to ecological models of performance – has made it possible to describe in increasingly detailed terms the constraints that guide athletes' behaviour during competition (McGarry et al., 2002; Rein & Memmert, 2016). However, this analytical refinement has also highlighted how decisions made under time pressure, often in conditions of perceptual uncertainty, represent one of the main factors discriminating between levels of expertise. This concept provides substantial data indicating that cognitive functions are crucial in the performance of open-skill sports, especially within professional athletics. Research on footballers, basketball players, and team sport athletes indicates that distinctions between elite and sub-elite athletes primarily manifest in selective attention, anticipation, working memory, and decision-making, rather than in fundamental motor skills (Vestberg et al., 2012; Voss et al., 2010; Huijgen et al., 2015). Given the evidence of the influence of executive functioning on the achievement of successful performance in athletes, this thesis aimed to deepen the effect of sport specific cognitive motor training on cognitive aspects of competitive athletes. In fact, although the influence of cognitive functioning on sports performance is recognised, few studies have focused on possible cognitive training methodologies. A significant contribution to overcoming this gap is represented by studies on CMDT developed by our laboratory and initially applied in basketball. Lucia et al. studies shown that training protocols that simultaneously integrate cognitive and motor demands produce improvements in athletic performance and in the neurophysiological correlates of action preparation (Lucia et al., 2022; 2023a; 2023b). However, the implementation of these protocols in a real-world setting still had limitations related to the ecology of training and the control of cognitive variables. In this regard, we have attempted to reinforce the CMDT methodology by utilising virtual reality technology. The results of this thesis suggest that the integration of CMDT and virtual reality represents a substantial methodological advance for cognitive training in sport. Virtual reality allows the implementation of immersive, controlled and reproducible environments, while maintaining high ecological validity (Faubert, 2013; Michalski et al., 2019). Several studies have shown that VR

may stimulates anticipation, decision-making and sensorimotor integration processes in a more targeted way than traditional training (Romeas et al., 2016; Wood et al., 2020). In line with this evidence, the results of this thesis indicate that CMDT protocols implemented in a virtual environment can selectively modulate the neural correlates of cognitive performance, producing measurable improvements at both the behavioural and electrophysiological levels. In this perspective, technology does not act as a simple accessory tool, but as a methodological enabler, making components of performance that were previously difficult to isolate trainable. Future implications include the development of personalised protocols, longitudinal monitoring of neural adaptations, and closer integration between neuroscience, athletic training, and high-level sport. Consistent with our hypotheses, both the young adult population and the professional footballers and dancers involved as experimental subjects in the research presented in this thesis reported significant neural and behavioural benefits following the proposed VR CMDT.

From a purely practical point of view, my doctoral path allowed me to create a small enterprise (Goalmind S.r.l.) that was founded based on the experimental results found in this thesis. This innovative start-up aims to develop VR cognitive motor training software for professional athletes. Currently, the first software developed by this young Italian company is used in the training routines of amateur and professional footballers, with cognitive and behavioural benefits. This example represents a concrete transformation and tangible application of a set of experimental data. The overall results of this thesis open various important future prospective, both in theory and in practice, contributing to the development of new areas of research in the field of sports neuroscience and CMDT training. Firstly, the data suggest the need to strengthen an integrated approach to training, in which cognitive, motor and decision-making components are not considered as independent or juxtaposed domains, but as functionally interdependent processes that cooperate in the construction of sporting performance. The evidence presented here supports a model in which cognitive processes are not simply ancillary to motor performance, but rather structural elements of sporting behaviour, intrinsically linked to the execution of technical movements and the regulation of action in dynamic contexts. From this perspective, cognitive training does not replace or compete with traditional motor training, but integrates synergistically with it, supporting the optimization of the perception-decision-action cycle that characterises open-skill sports.

This approach is consistent with contemporary performance models based on cognitive and ecological neuroscience, according to which the athlete's adaptation emerges from the continuous interaction between neural, bodily and environmental constraints.

Limitations

Although the results of this thesis are encouraging, certain methodological and conceptual limitations must be considered when interpreting the data. Firstly, although adequate based on statistical power estimates and in line with EEG/ERP studies in the field of sport, the sample size of the included studies was relatively small. This could limit the generalisability of the results to larger and more diverse populations. In particular, the experimental sample in the studies conducted on footballers was exclusively male and adolescent. At the same time, research on dancers showed a clear predominance of young adult females. These aspects could make it prudent to extend the conclusions to athletes of a different gender from the experimental group to different age groups or to higher (elite) or lower (amateur) levels of expertise. A second limitation concerns the specificity of the cognitive task used. The cognitive paradigm administered, although validated and widely used to investigate attentional, decision-making and anticipatory processes using ERP, represents an indirect measure of cognitive skills expressed in complex ecological contexts such as sports competition. Therefore, although the changes observed at the behavioural and electrophysiological level suggest an enhancement of functions relevant to football and dance performance, it is not possible to establish a direct and linear transfer to competition behaviour, an aspect that should be explored in future studies using on-field performance metrics or match analysis. A further limitation concerns the duration and frequency of the virtual reality training protocol. The training was administered once a week for eight weeks, a choice dictated by organisational constraints and the need to integrate it into the team's standard training workload. Although this dosage proved sufficient to produce significant effects, it does not allow for the exploration of possible dose-response relationships, nor does it determine whether more intensive or prolonged protocols could induce more marked or stable neural adaptations over time. From a neurophysiological point of view, the study focused on several ERP components (P1, N1, pP1, P3; pN and BP), selected based on solid theoretical and methodological foundations. However, this choice does not allow us to capture the entire spectrum of neural processes involved in the

cognitive-motor adaptation induced by VR training. In particular, complementary analyses, such as functional connectivity measures, oscillatory dynamics, or multimodal approaches (e.g., EEG–fNIRS), could provide a more integrated view of the underlying mechanisms. Finally, the absence of longitudinal follow-ups should be considered, as this prevents the assessment of the persistence of the observed effects in the medium to long term. The question therefore remains open as to whether the behavioural and electrophysiological changes induced by virtual reality training reflect transient adaptations or genuine stable modifications of cognitive and anticipatory systems. Overall, these limitations do not invalidate the internal validity of the study, but clearly outline future directions for research, suggesting the need for longitudinal studies with larger and more diverse samples, differentiated training protocols, and more ecological outcome measures in order to consolidate the role of virtual reality as an evidence-based tool for cognitive-motor training in sport.

Conclusions and research perspectives

This doctoral thesis sought to investigate the cognitive and neurophysiological mechanisms underlying athletic performance in open-skill sports, and to expand the analysis of the benefits of cognitive-motor dual-task training protocols by implementing them using VR technology. To date, the literature confirms that success in high-level sports performance does not depend solely on motor and technical aspects, but on the efficiency with which the mind system integrates perception, cognition and action in highly unpredictable contexts. Starting from this premise, the studies presented in this paper have progressively explored the impact of VR on cognitive-motor plasticity, analysing how immersive training can modulate the electrophysiological correlates (ERPs) associated with anticipation, sensorimotor integration, and decision-making. Overall, the research conducted confirms that cognitive-motor training in virtual reality represents a powerful tool for stimulating brain plasticity linked to executive and decision-making functions.

Specifically, in the first study conducted on young adults, aimed at validating a cognitive-motor training paradigm in virtual reality, named Rezzil Reaction Training, based on visuomotor readiness and perceptual discrimination exercises, significant effects were observed both at the behavioural level (improvement in reaction times and accuracy) and at the electrophysiological level, with an increase in the anticipatory pN and BP components. These results confirmed that cognitive training in VR can induce anticipatory functional plasticity, demonstrate the

effectiveness of such protocols, and lay the foundations for extending the paradigm to sport-specific contexts.

The second study, conducted on semi-elite young footballers, showed that integrating a sport-specific CMDT protocol in VR into the traditional training programme produced significant improvements in reaction times and cognitive response accuracy, accompanied by an increase in prefrontal and premotor anticipatory ERP components (pN and BP). These results suggested an enhancement of top-down control and motor preparation, central functions in the processes of anticipation and action planning (Di Russo et al., 2019; Lucia et al., 2023a). In the third study, the analysis was extended to post-stimulus components, highlighting an increase in pP1 — an index of perceptual-motor integration — and P3, associated with decision-making and stimulus categorisation. These changes, in the absence of variations in early perceptual components (P1, N1), indicate that the effect of training does not manifest itself as a generic increase in brain activity, but as a selective functional restructuring that optimises the efficiency of the cognitive processes involved in transforming information into action.

Before analysing the influence of these training protocols on a group of professional dancers, given the limited results available in the literature on the neural correlates typical of dancers, we decided to conduct an initial study, fourth research in this document, with the aim of identifying the ERP components that distinguish dancers. In this regard, in the subsequent study, we analysed the neural correlates of a group of professional dancers, comparing them with a general sports population. The marked difference observed in the anticipatory pN component suggests that dancers adopt a strong predictive cognitive control strategy, likely refined through years of exposure to complex choreographic tasks characterized by intense attentional demand and rapid response. Such an increase in pN could explain the concomitant reduction in reactive P1 and pP2 components, highlighting how more effective anticipatory preparation reduces the need for neural recruitment in later perceptual-decisional phases. In parallel, the increase in pP1 in dancers confirms the key role of sensorimotor integration in choreographic expertise. In this domain, the ability to transform visual, auditory, or proprioceptive sensory stimuli into smooth and synchronized motor actions represents a central competence, supported by specific neural processes already in the early post-stimulus phases. Given these results, we set up a fifth and final research project aimed at analysing the influence of a specific sport, CMDT-VR, on the cognitive performance and specific motor skills of a group of professional dancers. The results showed a significant improvement in both

response accuracy and postural balance. These behavioural effects were accompanied by an increase in anticipatory activity in the prefrontal cortex, indicated by an increase in the amplitude of the pN component. Again, this suggests an enhancement of top-down proactive control processes and inhibitory functions, which have previously been associated with this component. In contrast, motor preparation and response times did not show significant changes following training.

From an application perspective, the results of this thesis suggest that virtual reality can be a strategic complement to traditional sports training, integrating the cognitive dimension into technical and tactical preparation. The use of CMDT protocols in VR allows executive functions to be trained in an immersive, safe and highly controllable environment, exposing the athlete to decision-making, anticipation and attention management tasks like those encountered during competition, but with the possibility of intensive repetition and immediate feedback. This methodology appears particularly useful in the training of young athletes, whose brains are at their most plastic and for whom cognitive training can make a decisive contribution to the development of more flexible and adaptive playing strategies. Furthermore, the use of VR allows for the customisation of cognitive and motor loads, providing coaches and sports psychologists with an objective tool for monitoring athletes' progress, analysing response time dynamics and identifying any areas of cognitive or attentional weakness.

On a scientific level, the results of this thesis support the prospects for studying the relationship between cognition and athletic performance, increasing attention on the importance of shifting the focus from purely motor training to an integrated paradigm, in which the mind and body are trained simultaneously as parts of a single adaptive system.

As for future developments, it will be essential to investigate the transferability of cognitive skills learned in a virtual environment to real-world performance. This objective requires longitudinal protocols and ecological measures of athletic performance to verify whether the improvements observed at the electrophysiological and behavioural levels translate into an actual competitive advantage. In addition, the optimal parameters of training intensity, frequency and duration, as well as inter-individual differences in neural response to VR, should be explored to define more precise and personalised protocols.

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