



## Review

## Transcranial electrical stimulation for procedural learning and rehabilitation

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## ABSTRACT

Procedural learning is the acquisition of motor and non-motor skills through a gradual process that increases with practice. Impairments in procedural learning have been consistently demonstrated in neurodevelopmental, neurodegenerative, and neuropsychiatric disorders. Considering that noninvasive brain stimulation modulates brain activity and boosts neuroplastic mechanisms, we reviewed the effects of coupling transcranial direct current stimulation (tDCS) with training methods for motor and non-motor procedural learning to explore tDCS potential use as a tool for enhancing implicit learning in healthy and clinical populations. The review covers tDCS effects over i. motor procedural learning, from basic to complex activities; ii. non-motor procedural learning; iii. procedural rehabilitation in several clinical populations. We conclude that targeting the primary motor cortex and prefrontal areas seems the most promising for motor and non-motor procedural learning, respectively. For procedural rehabilitation, the use of tDCS is yet at an early stage but some effectiveness has been reported for implicit motor and memory learning. Still, systematic comparisons of stimulation parameters and target areas are recommended for maximising the effectiveness of tDCS and its robustness for procedural rehabilitation.

## 1. Introduction

Procedural learning consists of the acquisition of motor and non-motor skills (e.g., habits or cognitive skills) through a gradual process that increases with practice, it is usually slower than declarative learning, requires fewer attentional resources and it is not accessible to consciousness recollection (Koziol & Budding, 2012; Knowlton et al., 2017). The ability to acquire new motor and cognitive skills during adulthood relies on the fact that the brain maintains plasticity even in old age (Greenwood & Parasuraman, 2012).

Considering that electrical stimulation can boost neuroplastic mechanisms (Bolognini et al., 2009; Monte-Silva et al., 2013; Simis et al., 2013), it is argued that such techniques can complement motor and cognitive training by magnifying natural plasticity processes, such as long-term potentiation (Ranieri et al., 2012; Nitsche et al., 2008). In particular, transcranial direct current stimulation (tDCS) is a noninvasive brain stimulation technique that delivers prolonged weak, direct electric current through electrodes positioned on the scalp, leading to cortical hypo- or hyper- polarisation according to specified parameters (Nitsche et al., 2008). Arguably, anodal stimulation typically increases

neural firing, while cathodal stimulation has the opposite effect (Nitsche et al., 2008). However, these effects are not linear and may vary according to the brain's basal state and the density of the applied current, which is associated with the intensity of the current, electrodes size, and duration of application (Batsikadze et al., 2013; Lapenta et al., 2013). Still, many studies demonstrate that the technique can modulate brain activity and has potential clinical use (Lefaucheur et al., 2017). Accordingly, because long-term potentiation (LTP) is argued as a main physiological foundation for learning (Riout-Pedotti et al., 2000), coupling brain stimulation to training methods is a promising avenue to accelerate learning, reducing the training period for acquiring motor and cognitive skills in complex tasks (Parasuraman & McKinley, 2014).

The brain networks involved in procedural learning differ according to the resources needed to accomplish each specific complex task. Although several data sources converge to indicate the involvement of the basal ganglia, the cortico-subcortical loops differ, especially when comparing motor and non-motor procedural tasks. In this extensive review, we aim to address motor and non-motor procedural learning experiments conducted with tDCS and explore its potential role as a tool for enhancing procedural rehabilitation in clinical populations. Previous

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reviews were either not specific for tDCS on implicit learning; or focused on specific procedural motor or non-motor tasks, or particular populations (e.g., Brunoni et al., 2012; Morya et al., 2019; Narita et al., 2020; Qi et al., 2022). The key insights presented here distinguish this review from previous ones by providing a comprehensive overview of the technique's applications on i. both motor and non-motor implicit learning, ii. across various populations, including healthy individuals and those with neurological disorders and, iii. by offering detailed tDCS parameters employed in the reviewed studies. The need to systematise tES protocols is a common argument in the field; yet, research applying entirely different protocols often emerges. Therefore, we emphasise the importance of understanding the optimal parameters for tDCS to maximise its potential in procedural rehabilitation. We hope that this review provides sufficient detailed information to encourage systematic comparisons of these parameters and guide new studies in selecting parameters that appear most effective for each population and behaviour. Overall, we aim to offer a comprehensive overview of the current state-of-the-art of tDCS in enhancing procedural learning, emphasising the need for further research to understand its effects and optimise its therapeutic application fully. Information will be divided into three main sections for didactical purposes. The first section covers tDCS use on motor procedural learning, including simple motor tasks and specific activities, such as sports and music. The second section reviews the application of tDCS on non-motor procedural learning, including findings on memory and prediction tasks. Finally, the third section will discuss initial findings and perspectives for the use of tDCS in procedural rehabilitation in clinical populations including major depression, Parkinson's disease, stroke, and psychotic patients.

## 2. Section 1. Motor procedural learning

Motor learning entails improving motor actions through practice (Dayan & Cohen, 2011; Wolpert et al., 2011). Learning and memory for perceptuomotor skills represent motor procedures learned through experience and can be described as procedural or non-declarative, representing a set of condition-action links (Knowlton et al., 2017). Movements are planned according to spatial aspects of the environment, are tied to specific effectors, and their control depends on proprioceptive feedback. Thus, learning motor procedures involves planning, executing, and integrating sensory feedback into motor behaviour (Knowlton et al., 2017). Further, sequential motor learning is critical in numerous skills ranging from simple tasks, such as pressing a button, to complex activities like piano playing (Keele et al., 2003).

Motor performance is typically assessed by examining the trade-off between speed and accuracy for a given task (Reis et al., 2009). The learning process can be further explored by evaluating the learning curve, i.e., how fast participants increase performance until reaching a plateau. Moreover, it is possible to evaluate learning online, i.e., the immediate effect of practice on motor skills (Brashers-Krug et al. 1996), and offline, i.e., the long-term effect of practice after consolidation, establishing or enhancing motor memories for a more extended period after training (Walker et al. 2003; Diekelmann & Born 2007; Romano et al., 2010). It is important to highlight that, in the tDCS literature, the terms "online" or "offline" refer to the stimulation being applied concurrently with or before the task, respectively. However, as we explained, we will adopt those terms referring specifically to the motor learning assessment.

Different brain regions are engaged in motor learning according to the task and the learning phase (Dayan & Cohen, 2011). Importantly, data from studies of impaired motor (Heindel et al., 1988, 1989; Harrington et al., 1990) and non-motor (Knowlton et al., 1996; Shohamy et al., 2004) procedural learning in patients with Parkinson's or Huntington's disease point to the basal ganglia as an essential system to procedural learning. It is argued that integrating feedback during learning may be a key feature of striatal-dependent learning (Aron et al., 2004). Considering the strong functional connectivity of the basal

ganglia with other brain areas (Cole et al., 2010) and particularly the influence of the corticostriatal loop on motor cortical plasticity (Knowlton et al., 2017) in the acquisition of motor skills, studies with brain stimulation typically target cortical motor areas, mainly the primary motor cortex (M1), a key area engaged in acquisition and consolidation of motor learning which is deeply related to its plasticity (Classen et al., 1998; Karni et al., 1995), but also the premotor cortex (PMC) and cerebellum. In alignment, a recent systematic review including 11 articles on tDCS and motor skills points out improved motor learning, mostly evidenced by reduced time to complete motor tasks, after stimulation over one of the following: M1, left dorsolateral prefrontal cortex and right cerebellum (Qi et al., 2022).

### 2.1. Modulating procedural learning of sequential actions

Most studies on motor procedural learning apply a serial reaction time (SRT) task where the participants observe a series of cues and respond with their hand fingers according to the stimulus's location. When the sequence of stimuli follows a pattern, the sequence is implicitly learned, and reaction time decreases. It's important to note that while often referred to as 'motor learning', SRT tasks encompass visuomotor learning rather than purely motor learning, as the ability to learn sequences can occur through observation of stimuli, even without direct motor output (Pedraza et al. 2023). It is argued that a dorsal system, including parietal and supplementary motor cortices, is involved with implicit learning and stimuli association, whereas a ventral system, including temporal and lateral prefrontal cortices, is involved with both implicit and explicit learning (Keele et al., 2003), which is crucial information for defining target areas for brain stimulation.

In this sense, Nitsche et al. (2003) evaluated the effects of 15 min of anodal, cathodal, and sham tDCS over four areas: (i) the M1, (ii) the PMC, (iii) and the lateral or (iv) the medial prefrontal cortices (PFC). The tDCS (1 mA, 35 cm<sup>2</sup> electrodes) was applied concurrently with an SRT task throughout the experiment. The choice for M1 is quite straightforward, and the rationale for modulating frontal areas arises from the knowledge that the priming of signals incoming from these areas is involved in implicit learning processes (Hazeltine et al., 1997). Besides showing a performance increase across trials in all conditions, the anodal M1 group had significantly enhanced performance, and there was also a trend in the same direction for cathodal stimulation. While the anodal effect was not surprising in the light of evidence that it increases the excitability of neuronal output in underlying cortical areas (Nitsche et al., 2008) and that the activity of M1 is critically involved in the early phase of procedural motor learning (Mullbacher et al., 2002), the trend for cathodal stimulation was unexpected and speculated by the authors to reduce noise by "focusing" cortical activity onto the neurons involved in the learning process. However, it is essential to emphasise that the current density, determined by several parameters, such as the size of electrodes, the current intensity, and the stimulation's duration, may determine the behavioural outcome. Thus, an alternative explanation for Nitsche et al. (2003) cathodal findings could rely on the duration of stimulation. In fact, an elegant study compared within-subjects effects of anodal, cathodal, and sham stimulation (2 mA, 35 cm<sup>2</sup> electrodes) in the first 13 min and after this period during the STR task (Shilo & Lavidor, 2019). For the first 13 min of the task, anodal stimulation led to faster performance than cathodal and sham. However, after 13 min of the task, this pattern switched, and participants became faster with cathodal stimulation (Shilo & Lavidor, 2019). This switched pattern according to the stimulation length agrees with previous findings of the non-linear effects of tDCS on the motor cortex (Batsikadze et al., 2013). Finally, it could also have been a chance finding, as the study's sample size was small and only a trend was found.

In turn, Rivera-Urbina et al. (2022) evaluated the effects of tDCS over M1 and posterior parietal cortex (PPC) in an attempt to disentangle the contribution of each of these structures in early and late motor learning

stages. Each subject participated in four-session, each consisting of two consecutive days of sessions receiving anodal or sham stimulation over the two different cortical areas, the left PPC and left M1 (5 mA, active electrode of 20 cm<sup>2</sup>, reference electrode 35 cm<sup>2</sup> over the contralateral supraorbital area). However, participants were divided into two groups: stimulation was applied either in the first (early stage) or second (late stage) testing day stage of motor learning. They found a specific target and timing effect, i.e., only anodal stimulation over the PPC, and when applied in the late stage of learning, improved performance at the SRT task. This suggests that PPC is critical during the late motor learning stage, a memory reactivation period, but not relevant in initial learning, which is crucial for optimising stimulation protocols in rehabilitation and clinical contexts (Rivera-Urbina et al., 2022).

Since the decline in motor performance is naturally associated with normal ageing, there is interest in understanding the potential effects of tDCS on improving or maintaining motor abilities in the elderly. In the context of implicit motor learning, two recent studies evaluated the potential effects of tDCS. Abedi and colleagues (2022) assessed the effects of 20 min of anodal tDCS over M1 during SRT task in low-activity older adults (mean age 69.92 years) over five consecutive days. Response times and error rates were measured before, immediately after, one day after, and one week after the intervention. Results indicated significant improvements in both groups over time, but no significant differences between groups at any time point (Abedi et al., 2022). This suggests that while SRT task training enhances learning, the stimulation did not provide additional benefits for low-activity older adults. Another study using a similar approach tested different intensities (1, 2, or 3 mA) of anodal tDCS over the left M1 (35 cm<sup>2</sup> electrodes, reference over the contralateral supraorbital area) during the SRT task. Only under 2 mA anodal stimulation was there a significant reduction in reaction time in all sequence blocks compared to the random block, suggesting more stable motor learning. No significant differences in error rates or reaction time variability were found, which the authors suggest could be due to different methodological approaches compared to previous findings in young adults (Ghasemian-Shirvan et al., 2023). These studies suggest that age-related changes in brain function and structure might result in differential effects of tDCS over M1 on motor learning and highlight the need for adapted stimulation protocols for the elderly.

The possibility of increasing motor procedural learning with tDCS was also evaluated by combining brain stimulation with motor imagery (Debarnot et al., 2019). Combining 13 min of M1 anodal or sham tDCS (2 mA, active electrode 25 cm<sup>2</sup>, reference electrode 35 cm<sup>2</sup>) with a motor sequence, practised either physically or via imagery for three consecutive days, Debarnot et al. (2019) evaluated general motor skill and sequence-specific learning effects. For general motor skills, i.e., reaction time (RT) and accuracy for detecting whenever an asterisk appeared under a letter, participants seemed to reach a ceiling effect in the first session and no tDCS effects were reported. For sequence learning, though, a consolidation process across successive days of training sessions was observed for all groups, with physical practice having more substantial effects compared to imagery. In turn, during the first session, anodal compared to sham tDCS increased sequence-specific performance (i.e., RT and accuracy detecting when an asterisk indicated two target letters presented in a sequence-specific fashion) when combined with motor imagery, but not with physical training. The single-session effect of tDCS combined with imagery introduces exciting possibilities for rehabilitation interventions by coupling brain stimulation and imagery for people with reduced mobility (Lapenta et al., 2011). Finally, multiple sessions of anodal tDCS coupled with both tasks led to better sequence-specific performance compared to a single stimulation session showing specific cumulative effects of tDCS over M1 on implicit motor learning (Debarnot et al., 2019).

Attempting to uncover the roles of M1 and PMC and the potential benefits of brain stimulation over these areas, Kantak et al. (2012) tested online and offline (immediately after and the following day) effects of

anodal and sham stimulation in groups, receiving stimulation over right M1 or dorsal PMC (1 mA, active electrode 8 cm<sup>2</sup>, reference electrode 48 cm<sup>2</sup>) during an SRT task performed with the left hand. They found that anodal stimulation over the M1 increased online performance. Regarding the offline effects, evaluation the following day revealed that anodal tDCS over M1 significantly improved retention performance, whereas, over dPMC, it attenuated consolidation of the motor sequence compared with sham and M1 stimulation. These effects differ from the increased dPMC excitability during the immediate post-practice period and better offline performance produced by repetitive transcranial magnetic stimulation (TMS; Boyd & Lindsell, 2009). Notably, the TMS study applied stimulation over the left hemisphere as opposed to Kantak et al. (2012), who stimulated the right hemisphere. Most studies targeting M1 show consistent effects of neuromodulation when stimulation is applied contralaterally to the movement, irrespective of the subject's laterality. On the other hand, interesting hemispheric differences have been demonstrated by stimulating more frontal areas. Whereas anodal stimulation (2 mA, 25 cm<sup>2</sup> electrodes) over left PFC was demonstrated to have similar effects when applied to the M1 contralateral to the hand used to perform the task, i.e., faster learning rate and shorter reaction time for implicit learning, right PFC stimulation seems to slow response times across trials (Greeley & Seidler, 2019). Such findings suggest complex and hemisphere-specific roles of frontal cortical areas in sequence learning, thus indicating that stimulation over contralateral M1 and left, but not right, frontal areas can benefit learning under implicit conditions.

Notably, the timing of tDCS delivery seems crucial to determining retention effects. Studies that found positive, long-lasting effects, i.e., hours or days after stimulation, were those where stimulation was applied concurrently with training. Otherwise, when stimulation over M1 is delivered after the training, performance is enhanced when participants perform the task immediately after stimulation (Tecchio et al., 2010; Chen et al., 2020) but not after more extended periods (Chen et al., 2020).

A systematic review and meta-analysis evaluated 13 articles and 20 studies using tDCS over M1 during procedural motor learning tasks (Hashemirad et al., 2016). They found no significant changes in the accuracy of motor sequence learning after the application of either unilateral or bilateral M1 stimulation, while a significant change was seen at the retention phase for unilateral stimulation of contralateral M1 in SRT tasks, but not in sequential visual isometric pinch (SVIP) tasks (Hashemirad et al., 2016). Most interestingly, multiple sessions (3–4 days) of anodal tDCS significantly improved motor skills at the post-intervention and retention phases for SRT tasks (Hashemirad et al., 2016). In turn, for SVIP tasks, multiple anodal tDCS sessions produced significant effects at post-intervention but not retention time points (Hashemirad et al., 2016). The same group empirically tested tDCS effects over three different areas (M1, DLPFC and PPC) on reaction time during SVIP (Hashemirad et al., 2024). Anodal stimulation (0.3 mA for 20 min, active and reference electrodes: 3 cm<sup>2</sup> and 12 cm<sup>2</sup>, respectively) was administered concurrently with the SVIPT, which required participants to precisely control their forces to reach seven different target forces between 10 % and 40 % of the maximum voluntary contraction. Participants' RTs were evaluated through four test blocks at baseline and 15 min after the intervention. They found no significant effects for DLPFC and PPC stimulations compared to sham. Curiously, M1 stimulation impaired RTs, indicating again that a single session of anodal tDCS over M1 may not suffice to improve performance in this type of motor task (Hashemirad et al., 2024). Furthermore, it could be argued that reducing electrode size to improve technique locality might not always result in better performance outcomes, as also shown by Firouzi and colleagues (2023).

Another area involved in the movement is the cerebellum (Kitazawa et al., 1998), and patients with cerebellar lesions have significant impairments in procedural motor tasks (Doyon et al., 1997; Molinari et al., 1997; Shin and Ivry, 2003). Further, cortico-cerebellar connectivity,

along with increased striatal activation, has been related to performance in motor sequence learning tasks (Steele and Penhune, 2010). However, its precise role in motor learning is unclear (Seidler et al., 2002). In the first investigation of cerebellar tDCS, Ferrucci et al. (2013) applied 20 min of anodal and sham stimulation (2 mA, 35 cm<sup>2</sup> electrodes) after SRT training and immediately resumed the task. Comparing stimulation type and pre-post conditions, they found that performance was similar before but differed after stimulation. Specifically, anodal stimulation increased performance, indicating the cerebellum as a potential target for interventions for implicit motor learning. (Ferrucci et al., 2013). A recent study evaluated the effects of 20 min of anodal, cathodal, and sham tDCS (2 mA, 35 cm<sup>2</sup> electrodes) delivered to the cerebellar hemisphere ipsilateral to movement in the SRT (Shimizu et al., 2017) and evaluated performance immediately after and 24 h after training. No effects were observed at the post-stimulation measurement. No effects were observed immediately after the training, but after 24 h, the cathodal group showed worse performance than the anodal and sham groups, and gains were most remarkable in the anodal group. The results corroborate what is known about the cerebellum, in connection with other cortical and subcortical motor areas, having a specific role in motor sequence learning and generalisation, and demonstrate that these processes can be boosted with anodal tDCS over the cerebellum (Shimizu et al., 2017). Importantly, this protocol extends the Ferrucci et al. (2013) findings by showing opposite effects for cathodal and anodal stimulation, showing polarity-specific effects of tDCS over the cerebellum for motor procedural learning. Furthermore, the results by Shimizu et al. (2017) align with brain stimulation studies over M1 in that motor gains are more robust and more clearly observed after consolidation. Moreover, during- and post-training stimulation protocols using anodal polarity have been shown to be effective. These studies combined introduce the possibility of targeting the cerebellum for procedural learning rehabilitation protocols with electrical stimulation.

Summarising the data presented in this section, we can conclude that M1 seems to be a crucial node in the procedural motor learning network and that the application of electrical stimulation over this area has a potential for consolidation and, thus, long-term effects, at least in some motor learning tasks. Moreover, M1 effects are task and dose-dependent. Specifically, regarding the tasks, it must be considered that so far, most studies have used SRT tasks either with detection of target stimuli or sequence production and, therefore, more studies are needed in order to clarify tDCS potential in other types of tasks involving implicit motor learning, such as sports and musical performance, which will be explored in the following section. Furthermore, tDCS application coupled with training is more effective when compared to after training. Concerning tDCS dosage, albeit multiple sessions versus a single session seem more beneficial to obtain retention effects, the main issue when considering tDCS effects on motor tasks is the lack of consensus regarding the parameters of stimulation, i.e., electrode size, montage, the intensity of current and duration of stimulation in each session. Some researchers argue that focal, compared to conventional, tDCS over M1 leads to the recruitment of distinct pathways and that more targeted stimulation approaches may improve outcomes (Iannone et al., 2022). Others found more robust effects using conventional tDCS (35 cm<sup>2</sup> electrodes) and speculate this might be due to a generalised stimulation of M1 or of adjacent associative motor areas (Firouzi et al., 2023). Moreover, effects could also be modulated by dopamine availability. Specifically, when examining the effects of multiple intensities of anodal tDCS over M1 with and without pharmacological administration of levodopa (l-dopa), Leow and colleagues (2024) showed that the placebo l-dopa group improved performance during explicit learning of motor sequences after 4 mA stimulation, whereas the real (100 mg of l-dopa) group showed decreased performance. Although their research was focused on explicit motor learning, similar mechanisms likely occur for implicit motor learning, suggesting a neurochemical basis for the dose-response relationship (Leow et al., 2024). Still, consistently replicating positive findings using a specific dosage is crucial. Therefore,

until such parameters for stimulation are well established, it is problematic to propose effective clinical interventions for rehabilitation purposes.

Finally, the specific role of PMC and cerebellum and the gains in brain stimulation over these areas in procedural learning are less studied and not yet well understood. Although the ipsilateral cerebellum and left premotor cortex are plausible target areas, their role in motor skill acquisition and retention is less clear. In this way, further investigations are needed to conclude the effectiveness of electrically stimulating these areas to boost implicit motor learning.

## 2.2. Modulating procedural learning and performance in sports and music

The studies of tDCS in procedural motor learning have prompted some researchers to evaluate the possibility of boosting skill learning and performance in sports and music. The idea of “tDCS doping” in sports is not new, and experiments in controlled laboratory environments have demonstrated its potential for reducing the perception of effort and fatigue, thus increasing muscular endurance (Reardon, 2016; Edwards et al., 2017; Morya et al., 2019). However, as motor learning plays a critical role in acquiring the motor actions necessary for high-performance sports (Nielsen and Cohen, 2008), the next step would be to evaluate the effects of electrical stimulation when learning sport-related skills.

A few studies have investigated the potential of electrical stimulation in the acquisition of sport-related skills. We will present only those that refer to procedural learning. For a review that includes studies on explicit learning and how tDCS can be translated into an applied sports enhancement context, refer to Fries et al. (2022). Zhu et al. (2015) hypothesised that cathodal stimulation of the left dorsolateral prefrontal cortex (DLPFC) could promote implicit motor learning due to the suppression of verbal working memory activity, reducing explicit verbal-analytical engagement in movement control. They assessed golf putting performance and verbal working memory before, immediately after, and the day after a training phase combining cathodal or sham stimulation (1 mA, 25 cm<sup>2</sup> electrodes) during golf putting and concurrent tone-counting tasks. There was an effect on verbal working memory immediately after training, where the sham group displayed increased counting recall, while the cathodal group had no significant change. This finding suggests that cathodal tDCS over the left DLPFC suppressed verbal working memory, but its negative effect on the counting recall task was cancelled by the positive effect caused by retesting familiarity. At the test phase (on the second day), the cathodal group showed increased performance, similar to the sham group, which maintained similar scores as the previous day. On the golf putting task, the cathodal stimulation group performed better at the training and test phases when compared to the sham group. Findings by Ambrus et al. (2020) suggest that the disruption of bilateral DLPFC using TMS enhances statistical learning of non-adjacent dependencies. Aligned with the competition theory, Zhu et al. (2015) effects are consistent with the claim that prefrontal cortex inhibition by cathodal tDCS may shift dominance from the declarative (explicit) memory system to the non-declarative procedural (implicit) system (McKinley et al., 2014), opening the possibility of increasing motor learning of sports in non-experts by suppressing explicit memory with cathodal stimulation.

In a different approach, Suzuki et al. (2017) aimed to improve audio-visual-motor integration and performance in a dance video game task. They applied 15 min of anodal, cathodal (1.5 mA, 35 cm<sup>2</sup> electrodes), or sham tDCS over the left medial-temporal gyrus (MTG) after a baseline assessment of dance performance which was subsequently re-assessed in three sessions of 30 s (apart from one another by 5 s rest) after stimulation. The number of accurately timed steps was evaluated as an index of performance over repetitive gameplay and between stimulation conditions. There was a general increase in performance due to training, as revealed by comparing the baseline with the third post-stimulation dance performance assessment. Further, participants with previous

musical or music game experience showed improved performance after anodal stimulation of the left MTG. These results suggest that anodal stimulation of the MTG might facilitate multimodal integration, leading to better accuracy in motor execution, but only in people who have already developed the cortical circuits for multisensory integration and corresponding motor output through previous music or music video game experience.

Also related to music, but concerning the aspect of playing instruments, to address the speculations on the possibility of enhancing the motor skills of experts in their musical performance, a group performed two experiments evaluating the effects of tDCS over fine motor control in skilled pianists. In a seminal study, [Furuya et al. \(2013\)](#) applied bihemispheric bipolar right anodal/left cathodal, left anodal/right cathodal, and sham tDCS over the M1 (2 mA, 35 cm<sup>2</sup> electrodes, for 24 min) during musical training where expert pianists were reproducing a sequence on the keyboard. Pianists' performance was assessed through speed and accuracy before and after the training coupled with stimulation. There was no main effect of training nor of active compared to sham stimulation on speed or accuracy. However, there was a significant correlation between the age at which pianists commenced piano training with the effects of practice combined with active stimulation on the performance of finger movements (i.e., decreased movement variability and shorter finger-key contact). Specifically, participants who started piano training later had a more substantial decrease in the temporal variability of keystrokes in the hand contralateral to cathodal stimulation, whereas anodal stimulation resulted in the quicker release of the fingers of the contralateral hand. Therefore, the earlier they started to practice piano, the less likely it was for tDCS to improve performance, which authors attributed to greater performance optimisation in more experienced pianists. In a second experiment, comparing pianists with musically untrained controls, contralateral anodal and ipsilateral cathodal tDCS improved task performance in the non-musicians but caused deterioration in the pianists. These findings support that changes in dexterous finger movements induced by bihemispheric tDCS are expertise-dependent and may be ineffective for improving motor performance in tasks in which participants are already highly skilled ([Furuya et al., 2014](#)).

In sum, the study of electrical stimulation in acquiring sports and musical abilities is still at an early stage. Preliminary findings suggest the potential for boosting motor ability acquisition by coupling tDCS with training. Importantly, the strategies of the mentioned studies vary regarding the task, e.g., golf putting versus music dance game; area of stimulation, e.g., DLPFC versus MTG; tDCS dosage; and most importantly, the target network, e.g., shifting dominance from the declarative to the non-declarative procedural system versus audio-visual-motor integration. In turn, the experiments with skilled musicians suggest that tDCS effects are limited to initial learning and likely not applicable to improving athletic and musical performance in highly skilled individuals.

### 3. Section 2. Non-motor procedural learning

Procedural learning is also present in non-motor skills, for example, the so-called implicit category learning. If, on the one hand, we can learn and form mental categories (e.g., social categorisation) in an explicit and declarative way, i.e., through the conscious perception of characteristics patterns by experience or explicitly communicated by others; part of the processes of category formation take place by probabilistic association, i.e., based on the detection of characteristics of the different categories from continuous exposure or experience without any explicit instruction, which is supported by non-declarative memory mechanisms ([Knowlton & Squire, 1993](#)). This category formation occurs through the implicit learning of probabilistic events associating stimuli and outcomes. In general, such tasks require the participant to make predictions based on cues with different, unknown association rates with a set of outcomes.

#### 3.1. Modulating non-motor procedural learning

The first tDCS study aiming to enhance predictions based on precedent cues used the Weather Prediction Task, in which continuously presenting combinations of 4 different image sets holds probability to weather a sunny or rainy forecast that participants are asked to predict – the task thus promotes implicit learning by an association between cue card combinations and the weather outcome (sun/rain) therefore configuring an implicit memory test ([Knowlton, Squire, & Gluck, 1994](#); [Kincses, Antal, Nitsche, Bartfai, & Paulus, 2004](#)). In this particular study, the stimuli were not linked to the responses of sun and rain with certainty; instead, each stimulus was related to the responses at rates of 75 %, 57 %, 43 %, and 25 %. Thus, the combinations generated different probabilities for sun and rain. The study was conducted with 22 healthy participants divided into two groups, either with the active electrode over the left PFC (group 1) or over the occipital cortex (group 2), with the reference electrode over the vertex (Cz). Both groups received 10 min of 1 mA anodal, cathodal, and sham tDCS. The authors observed a significantly increased performance in group 1 after anodal tDCS, likely due to the involvement of left PFC in the task and the recruitment of subcortical structures through cortico-subcortical circuits described in previous studies ([Alexander et al., 1986](#)). This hypothesis is supported by results with rTMS applied over the PFC that have observed an increase in the concentration of dopamine in the caudate nucleus after rTMS over the PFC (e.g., [Strafella, et al., 2001, 2003](#)).

[Majidi et al. \(2017\)](#) also tested the effect of tDCS on implicit learning with the Weather Prediction Task targeting the PFC and cerebellum (2 mA, 5x7cm electrodes). Unlike [Kincses and collaborators \(2004\)](#), no effect of tDCS on task performance was observed for either target area ([Majidi et al., 2017](#)). These contradictory results may be related to a weak effect of tDCS on this kind of learning, as well as to differences in stimulation parameter values between protocols, the number of stimuli (i.e., trials) on the tasks employed by each study, in the experimental design and statistical treatment of data and the sample size. Once again, it is crucial that future studies systematically assess specific parameters over time since adopting very different parameters between studies limits the “communication” between their results and, so, the possibility of interpretation of joint results between experiments.

[Janacek et al. \(2015\)](#) investigated the hemispheric roles of the prefrontal cortex in statistical learning and the consolidation of acquired information during an Alternating Serial Reaction Time (ASRT) task. Unlike deterministic SRT tasks, which follow a fixed, predictable sequence, the ASRT introduces randomness or uncertainty into the stimulus sequence. In this study, participants received 10 min of anodal stimulation (1 mA, 5x7cm electrodes) over either the left or the right dorsolateral prefrontal cortex (DLPFC), with the reference electrode placed over Cz. Learning performance was assessed during stimulation, post-stimulation, and at 2- and 24-hour retention phases. Stimulation of the right DLPFC led to increased overall performance compared to sham stimulation, evident during both retention phases, while stimulation over the left hemisphere showed no significant improvement in any assessment. The authors concluded that enhancing the activity of the right DLPFC improved the ability to discern statistical regularities ([Janacek et al., 2015](#)).

Serial Reaction Time paradigms have also been coupled to tDCS in social and cognitive contexts, expanding its application beyond motor behaviour. Specifically, [Ma et al., \(2023\)](#) applied 20 min of anodal tDCS (2 mA, 35 cm<sup>2</sup> electrodes) over the posteromedial cerebellum during implicit learning of sequences of social beliefs of others (Belief SRT) and non-social coloured shapes (Cognitive SRT). Anodal compared to sham stimulation sped up response times in the Cognitive SRT during stimulation and also 30 min and 1 week after stimulation; indicating possible long-term advantages of cerebellar stimulation for cognitive functions. In turn, there was no significant improvement in the Belief SRT task, which the authors attribute to the task's familiarity and reduced mental effort demands, thus indicating a ceiling effect ([Ma et al., 2023](#)).

Concerning other paradigms applied in non-motor implicit learning, [Clark and colleagues \(2012\)](#) tested the effect of tDCS on a discovery-learning paradigm. Unlike the Weather Prediction Task, the discovery-learning paradigms are characterised by learning based on experience and repeated exposure to the environment where participants received only minimal instructions about the task, i.e., they would be in charge of a military mission in a middle-eastern country. In this study, the participants should see static images for 2 s and respond in 3 s if they found any potential threat in the picture, despite not being previously instructed about what type of threat or cues they should attend to. After each response, they saw a feedback video, where: in case of a false positive, they received a message warning they delayed the mission; in a false negative, they watched a video showing a bomb exploding or a sniper shooting (which gave a clue about the type of threat they should look for); and a correct positive/negative, with the video showing they progressing in the field and a voice praising their success. The authors carried out four experiments in which the positioning of the electrodes or the intensity of the applied current varied. In the first three experiments, an anodal electrode was positioned over the right inferior frontal cortex (rIFC) and the reference on the contralateral upper arm. Stimulation was delivered for 30 min using 11 cm<sup>2</sup> electrodes, and participants were divided into low-intensity (0.1 mA) or high-intensity (2.0 mA) groups (experiments 1 and 2), or the same both groups with an additional middle-intensity group (0.6 mA) in experiment 3. In the fourth experiment, the anodal was positioned over the right parietal cortex (reference over the contralateral upper arm) with an intensity of 2.0 mA. In all experimental groups, tDCS were applied 5 min after the beginning of the task, lasting for 30 min concurrently with the task. The researchers assessed participants' performance in all experimental groups immediately after training and after 60 min. They found improved performance for all high-intensity (irrespective of over inferior frontal or parietal cortex) immediately after training and 60 min after stimulation compared to low-intensity groups. Another important aspect of this study was the analysis of the improvement according to the intensity of the applied current. The authors found an improvement proportional to the stimulation intensity. Testing a dose-related effect is critical, but it has yet to be done by many studies.

Some of the authors of [Clark et al. \(2012\)](#) published three other articles adopting similar methods of experiments 1 and 2, i.e., anodal tDCS over the rIFC, while extending their previous findings. In the first study, [Coffman et al. \(2012a\)](#) showed an increased performance of threat detection again after high-stimulation (2 mA, 11 cm<sup>2</sup> electrodes) of the right inferior frontal cortex when compared to the low-stimulation (0.1 mA, 11 cm<sup>2</sup> electrodes) group. They also showed that the enhanced threat detection performance was correlated to increased alerting attention after testing the participants on the Attention Network Test ([Fan et al., 2002](#)), which assesses participants' performance over three attentional networks (alerting, orienting, and executive control). In the second study, [Coffman et al. \(2012b\)](#) investigated if the detected effect by [Clark et al. \(2012\)](#) on the rIFC would be modulated by a different number of novel or repeated stimuli between training and test; by type of blindness (single- or double-blind), or would by participants' expectation or mood. Again, high-intensity (2 mA, 11 cm<sup>2</sup> electrodes) anodal tDCS over the rIFC facilitated the learning to detect hidden objects, and this effect was increased for repeated stimulus. Finally, in the third study, [Falcone et al. \(2012\)](#) investigated whether tDCS modulated perceptual sensitivity, a measure widely used to assess learning and perceptual performance, and tested the learning effects after 24 h. In this study, 2 mA (11 cm<sup>2</sup> electrodes) tDCS over the rIFC increased perceptual sensitivity (it doubled compared to 0.1 mA) and accelerated learning. In addition, the effects were still observable 24 h after the tDCS session.

Finally, a study by [Mosbacher et al. \(2021\)](#) assessed the effect of two different transcranial electrical stimulation: the tDCS and the transcranial alternating current stimulation (tACS), on procedural learning of an arithmetic task. Briefly explaining the tACS, it is similar to a tDCS, except that it uses an alternating current instead of a direct current and

has an extra parameter beyond time and intensity – the frequency. Since the tACS can target specific frequency bands, one of its known mechanisms is modulating the entrainment of brain oscillations ([Reato et al., 2013](#)), which affects cognition ([Battleday et al., 2014](#)). However, the same mechanism can also occur in tDCS without specificity ([Hanley et al., 2016](#)). Regarding the study by [Mosbacher et al. \(2021\)](#), they had seven experimental groups that differed on tDCS or tACS montages: two for tDCS – anodal over the left DLPFC or the left PPC (1.0 mA, reference over contralateral supraorbital area); two for the alpha-tACS – targeting left DLPFC or left PPC (around 1.0 mA, adjusted for each individual; reference over left shoulder); and two for theta-tACS, identically to the alpha-tACS (see [Mosbacher et al., 2021](#) for specific consideration on how they adjusted intensity and frequency of each participant); and sham, where participants could use a montage similar to the tDCS or the tACS (the distribution of montages among participants were balanced). They compared the seven groups on an arithmetic task adapted from the “pound arithmetic” ([Rickard, 1997](#)), where participants should proceed with calculations to assess procedural or fact learning according to the type of arithmetical problem. The authors found that theta-tACS significantly decreased the number of trials necessary to achieve fact learning (compared to sham), and tACS (irrespective of alpha or theta) decreased calculation time during fact learning. There was no effect concerning procedural learning. The null effect for tDCS was not expected since previous studies showed its effectiveness for arithmetics learning ([Schroeder et al., 2017](#)). The authors proposed that the low intensity (1 mA) and differences in the montage (target and reference) or the task could be associated with those effects. Once again, those findings suggest the urge to systematically study different protocols, controlling and assessing how each parameter could interfere with tDCS outcomes.

Summing the findings for non-motor procedural learning, few studies assessed this topic, mostly evaluating anodal stimulation over prefrontal areas. While some studies reported significant effects of tDCS on the detection of hidden targets, there were inconsistencies in the results for the weather prediction task, and a null effect was observed for procedural learning on an arithmetic task. Furthermore, only stimulation of the right prefrontal area improved performance in statistical probabilistic SRT task, indicating a hemispheric differential role depending on the task type. These results underscore the importance of such tasks in investigating the role of the DLPFC, as [Vékony et al. \(2021\)](#) emphasised.

There is still a long avenue in this topic to fully comprehend how tDCS affects non-motor procedural learning. We stress the necessity of future studies to systematically investigate how different parameters (e.g., intensity, duration, electrode size, target area, etc.) could influence tDCS efficacy in this phenomenon. Despite the contrary findings, the effects of tDCS on implicit learning and perceptual sensitivity in healthy volunteers signal an essential avenue for studies of this technique in clinical populations, as described in the following section.

#### 4. Section 3. Procedural learning in the clinical population

Studies have consistently found procedural learning impairments in neurodevelopmental, neurodegenerative, and neuropsychiatric disorders. For example, a meta-analysis of studies that used the SRT found consistent impairment in this ability in dyslexia, developmental coordination disorder, schizophrenia, Parkinson's disease, and specific language impairment ([Clark & Lum, 2017](#)). In addition to the impairment of motor learning, probabilistic learning is also impaired in schizophrenia ([Vercammen et al., 2011](#)), dyslexia ([Gabay et al., 2015](#)), and cerebellar malformation patients ([Butti et al., 2024](#)). Procedural learning can also be impaired in other disorders, such as major depression (MD), both in the probabilistic ([Kunisato et al., 2012](#); [Mörkl et al., 2016](#)) and motor domains ([Aizenstein et al., 2005](#); [Exner et al., 2009](#); [Naismith et al., 2010](#)). Nevertheless, it is important to stress that not all studies in patients with major depression found impairments in

procedural learning, possibly due to diversity of aetiology, severity, or differences in the treatment (Mörkl et al., 2016). Procedural learning impairments exist on the paretic side of stroke, as recently shown by a systematic review with *meta-analysis* (Kal et al., 2016). Finally, other disorders have been suggested in the literature to have impairment of procedural learning; however, recent systematic reviews of Autism Spectrum Disorder (Foti et al., 2015; Clark & Lum, 2017; Obeid et al., 2016), Alzheimer's disease (De Wit et al., 2021), and Korsakoff syndrome (Oudman et al., 2015) have not found reliable evidence of such impairment. Therefore, we will cover tDCS avenues for improving procedural learning in MD, Schizophrenia and other psychosis disorders, Parkinson, Stroke, and cerebellar malformation patients. In this particular section, when available we will first present an overall review of electrical stimulation effects (i.e., in behaviour and cognition) in each clinical group based on systematic reviews and/or *meta-analysis*, and then we will introduce the specific tDCS literature in procedural learning.

#### 4.1. Procedural rehabilitation for major depression

To our knowledge, only one study has evaluated the effect of tDCS on procedural learning in MD. In this study, Brunoni and colleagues (2013) compared active and sham left anodal/right cathodal tDCS (2 mA, 25 cm<sup>2</sup> electrodes, for 30 min) over the dorsolateral PFC during probabilistic classification learning of the weather identification task. Although accuracy increased along the task during sham stimulation, as expected, tDCS impaired the probabilistic learning in antidepressant-free MD patients (Brunoni et al., 2013). This contrasts with the aforementioned literature showing that anodal tDCS over left DLPFC improved probabilistic learning in healthy participants (Kincses et al., 2004). Regarding the difference with Kincses et al. (2004), Brunoni et al. (2013) suggested that the distinct effect of tDCS in MD patients compared to the control group was probably due to discrepancies in implicit learning strategy between both groups, where MD patients usually reveal lesser DLPFC activity during cognitive tasks. In this case, tDCS could be interfering with DLPFC activity and impairing proper integration of this area with striatum activity. It is also essential to notice that tDCS impaired the performance of patients with MD in other cognitive tasks associated with DLPFC activity, such as processing speed (Martin et al., 2018; Moreno et al., 2020), intelligence quotient, and perceptual reasoning (Sellers et al., 2015), what supports to a distinct effect of tDCS over DLPFC in MD patients in comparison to healthy participants.

Overall, tDCS can be considered a promising alternative therapy for MD patients (Bennabi & Haffen, 2018), however, more studies with larger samples are necessary to understand what its best therapeutic use would be as well as to comprehend better its effects on cognition along with its already known effect on MD symptoms. It is crucial that future studies emphasise controlling sample features such as characteristics of MD disorder (with or without melancholic features, uni- or bipolar, acute, or chronic) and the use of medication during the experiment. Based on the studies with healthy samples, it is also important to suggest that future studies with clinical samples attain similar parameters of tDCS, avoiding another confounding variable.

#### 4.2. Procedural rehabilitation for schizophrenia and other psychosis disorders

Several studies with randomised controlled trials (RCTs) have assessed electrical stimulation effects on schizophrenia, mainly tDCS studies with anodal over left DLPFC and cathodal over left temporoparietal junction, or bifrontal tDCS over DLPFC (anodal left/cathodal right), showing a significant effect of active over sham tDCS in the amelioration of negative symptoms and auditory hallucination, with marginal effect for positive symptoms (Cheng et al., 2020). However, the authors highlight that the effect of tDCS on auditory hallucination was considered insignificant after a sensitive analysis and should be

taken carefully (Cheng et al., 2020), with the best results in this domain occurring in response to a higher number of tDCS sessions (Kim et al., 2019). Regarding cognitive performance, a systematic review based on 32 studies pointed to a significant effect of active tDCS on attention, working memory, and social cognition (Kostova et al., 2020); however, a *meta-analysis* based on a subsample of 9 RCTs found only a significant effect of medium size of tDCS in working memory (Narita et al., 2020).

As regards the studies assessing tDCS effects on procedural learning in patients with schizophrenia, as far as we know, there is only one study investigating probabilistic learning (Vercammen et al., 2011). However, another study investigated tDCS effects on a motor learning task in participants with nonclinical psychosis (Gupta et al., 2018), which we will also debate since its findings can be translated to schizophrenia patients.

Vercammen et al. (2011) investigated the effect of anodal tDCS over left DLPFC (cathodal over the contralateral supraorbital area) in participants with schizophrenia responding to a weather prediction test, where the task was applied concurrently with the neuromodulation. Active stimulation of 2 mA intensity applied for 20 min improved procedural learning in part of the sample, specifically those who showed adequate learning at baseline. It is essential to highlight that this state-dependent effect of tDCS based on individual baseline performance has been reported in other studies with clinical and nonclinical samples (e.g., Benwell et al., 2015; Learmonth et al., 2015; Hsu et al., 2016; Norise et al., 2017; Dubreuil-Vall et al., 2019), and should be promptly considered in future tDCS studies in schizophrenia population.

In the study of Gupta et al. (2018), the authors assessed the effect of 2 mA anodal and sham tDCS over cerebellum during 25 min (using 35 cm<sup>2</sup> electrodes) in individuals with nonclinical psychosis (i.e., reporting high levels of psychotic symptoms) and healthy participants (control group) responding to a pursuit rotor task. In the sham condition, the nonclinical psychosis group showed impaired motor learning compared to the control group, whereas in the active tDCS condition, both groups performed similarly, indicating that anodal cerebellar tDCS improved motor learning in individuals with nonclinical psychosis. This result is promising to schizophrenia patients since this disorder, like other psychotic disorders, has been associated with cerebellar dysfunctions, despite not being limited to it (Andreasen & Pierson, 2008; Brady et al., 2019; He et al., 2019). Given this, it would be important for future studies to investigate the effects of cerebellar electrical stimulation on procedural learning in schizophrenia patients.

#### 4.3. Procedural rehabilitation for Parkinson's disease

Parkinson's disease (PD) is a neurodegenerative disorder that affects the motor system, impacting movement and motor fine control. In addition to those symptoms, it is also been consistently associated with impairment in procedural learning, as shown by various systematic reviews with *meta-analysis* (Siegert et al., 2006; Clark et al., 2014; Clark & Lum, 2017), however with few studies indicating that in some cases it can be preserved in PD (Ruitenberg et al., 2015; Deroost et al., 2018). In general, studies using electrical stimulation in PD usually apply tDCS over frontal lobe areas (i.e., PFC, supplementary motor area, PMC and M1), which leads to improvements in motor functions (Orrú et al., 2019; Simpson & Mak, 2019; Lee et al., 2019; Beretta et al., 2020), or over cerebellum, showing a short-term improvement on dyskinesia (França et al., 2018). However, it is important to highlight that a previous *meta-analysis* did not indicate any positive tDCS effects, at least for idiopathic PD (Elsner et al., 2016), so more RCTs are necessary to investigate further tDCS benefits and possible variables moderating its effect.

We identified six studies concerning the tDCS effect on procedural learning (Benninger et al., 2010; Ferrucci et al., 2016; Deroost et al., 2018; Horiba et al., 2019; Firouzi et al., 2021; Firouzi et al., 2024). Three did not find any effect of tDCS on procedural learning in PD patients assessed by SRT task, independent of anodal tDCS applied in motor or premotor areas (Benninger et al., 2010; Deroost et al., 2018) or

cerebellum (Ferrucci et al., 2016). Curiously, Deroost et al. (2018) did not find differences in SRT performance between PD and control groups in sham conditions and did not find any effect of active tDCS (1 mA, 19.25 cm<sup>2</sup> electrodes) on SRT performance in both groups. A systematic review also reported the spared procedural learning in PD patients (Ruitenberg et al., 2015), proposing that some studies have not found impairment probably due to a variety of PD features such as the severity of the disease and use of medications. Regarding the no effect of active tDCS on procedural learning, this is in line with previous literature on PD patients, however, it was not the case for healthy participants. To further analyse this issue, the authors ran a post hoc power analysis, which pointed to a lack of statistical power to detect minor effects and a Bayesian analysis that was inconclusive in the PD group to guide whether the authors could accept the null hypothesis, but indicated substantial evidence for no effect of active tDCS in the control group, what is contrary to the literature. Deroost et al. (2018) suggested that this could be due to differences in tDCS features in their study, such as smaller electrodes and low-intensity current, compared to the other studies in the literature which showed improved SRT performance of healthy participants in response to anodal tDCS over M1 (e.g., Nitsche et al., 2003; Kang & Paik, 2011). In addition, another aspect not seen by the authors and that could interfere is the number of sessions. Deroost et al. (2018) applied only two sessions of active tDCS, whereas improvements in older healthy participants were shown after multiple sessions of active tDCS (Dumel et al., 2016). Finally, it could also be the case that M1 stimulation impacts the consolidation but not the acquisition of implicit motor learning in PD, which was also reported by some aforementioned studies with healthy participants (also see Hashemirad et al., 2016 for a systematic review). On this matter, Firouzi et al. (2021) evaluated the effects of anodal, compared to sham, tDCS over M1 (2 mA, 46.02 cm<sup>2</sup> electrodes for 20 min) in a within-subjects design with PD patients with mild cognitive impairment on the acquisition (during stimulation), short-term (5 min post-intervention), and long-term (1-week post-intervention) consolidation of implicit motor sequence learning using the SRT task. This recent study showed no significant improvement during, a trend 5 min after and a significant effect one week after active stimulation (Firouzi et al., 2021). Subsequently, Firouzi and colleagues (2024) increased their sample of PD patients and added an age- and sex- matched control group without PD using the exact same protocol and evaluations (i.e., immediate, 5 min, and 1 week after tDCS). In their enlarged sample, they found that anodal tDCS facilitated sequence-specific learning when compared to sham in both groups. Furthermore, the effects were higher for patients with mild cognitive impairment when compared with those with intact cognitive status. Thus, at least for mild cognitively impaired PD patients, arguing in favour of the beneficial effects of tDCS on long-term consolidation of implicit motor learning (Firouzi et al., 2021, 2024).

Lastly, the study by Horiba et al. (2019) investigated when mirror visual feedback (MVF) could improve motor learning in PD who were more affected in one side of the body. The MVF is a technique first proposed by Ramachandran et al. (1995) as an easy and low-cost treatment for phantom limb pain, but also successfully adopted in motor rehabilitation of paretic hand in stroke patients (e.g., Altschuler et al., 1999; Yavuzer et al., 2008) and with the improvement of bradykinesia in PD patients (Bonassi et al., 2016). In this sense, Horiba et al. (2019) also assessed if 20 min of 2 mA anodal tDCS would improve motor skill acquisition along with MVF, testing active and sham tDCS in two groups of PD participants. First, the authors found that PD patients, compared to healthy controls, had impaired motor task learning using mirror visual feedback. However, anodal tDCS over M1 (contralateral to untrained hand) but not sham improved motor learning in PD, showing the benefits of tDCS applied concomitantly to a mirror visual feedback in this disorder.

#### 4.4. Procedural rehabilitation for stroke

Most clinical studies of electrical stimulation in motor rehabilitation were with stroke patients, with several systematic reviews published over the last years indicating positive effects of tDCS in their motor recovery (Kang et al., 2016; Orrú et al., 2020; Bornheim et al., 2020), including aphasia (Biou et al., 2019). On the other hand, other systematic reviews with meta-analysis did not find any effect of tDCS in the rehabilitation of the upper extremity after multiple sessions (Triccas et al., 2016) or in the improvement of spasticity (Elsner et al., 2017), walking, balance and postural control (Li et al., 2018; Kang et al., 2020). Those differences in the effectivity of tDCS and other NIBS across participants with stroke have been suggested to be related to inter-individual differences (Li et al., 2015), such as in the lesion and also in their structural reserve in cases of stroke, as proposed by the bimodal balance-recovery model, a model that tries to explain controversy between inter-hemispheric competition and vicariation models (Di Pino et al., 2014).

Regarding procedural learning in stroke, a meta-analysis indicated impairment in this domain on the paretic side, while it appears to be intact on the unaffected side of the body as indicated by the SRT (Kal et al., 2016). To our knowledge, only one study investigated tDCS effects on STR tasks (Talimkhani et al., 2022). In this study, patients with chronic unilateral stroke received anodal and sham (3 weeks apart) tDCS during SRTT for 3 consecutive days. The authors report that active stimulation increased performance in the task compared to sham and that participants reported minimal side effects (mainly itching and tingling under the electrodes). Further, stimulation and the three-day intervention time did not affect the patients' fatigue, attention, or pain (Talimkhani et al., 2022). Although the reported findings seem quite interesting for improving the rate of implicit motor learning of stroke patients, the authors do not report many stimulation parameters, including (and crucially) the stimulated area, which limits data interpretation and study replication. Given the lack of studies in stroke patients using classic tests such as SRT and weather prediction, we will further debate the findings of tDCS on motor rehabilitation with long-term retention of paretic limbs, which can be a general indicator of motor learning. One systematic review with meta-analysis specifically addressed this issue, based on 17 RCTs that investigated long-term retention of motor learning, assessing it at least five days after tDCS intervention (mean time of 43.8 days), suggesting a positive effect of tDCS in motor learning with long-term retention (Kang et al., 2016). However, it is essential to highlight that some studies found motor facilitation of tDCS but with no long-term retention (i.e., Hamoudi et al., 2018), or no tDCS effect at all, as already suggested by some meta-analyses (e.g., Triccas et al., 2016; Elsner et al., 2017). Future studies should focus on investigating inter-individual differences predicting the tDCS effect in patients with stroke, such as lesion size and location (Di Pino et al., 2014), baseline performance, and cortical excitability before neuromodulation (Li et al., 2015), and also adopting computational modelling to assess probable tDCS current flow through the brain (Brunoni, et al., 2012; Bestmann et al., 2015).

#### 4.5. Procedural rehabilitation for patients with cerebellar Malformation

Initially viewed as a motor structure, the cerebellum's involvement in a wide range of non-motor behaviours has been demonstrated for decades in neuroimaging and neuropsychological studies, supported by anatomical data (for a review, please see Strick et al., 2009). Moreover, it is thought to aid in developing and managing adaptive models of the environment by combining internally stored representations with external stimuli to optimise performance based on contextual requirements (Johnson et al., 2019).

Patients with cerebellum malformation show impaired predictive processing (Butti et al., 2024), leading to failure in predicting others' actions (Urgesi et al., 2021). In this line, Oldrati and colleagues (2024)

explored the effects of 20 min of anodal stimulation over the medial cerebellum (1.5 mA, using 25 cm<sup>2</sup> electrodes, reference on the right buccinator muscle) on social prediction abilities in adolescents and young adults with non-progressive, congenital cerebellar malformations (CM). Participants should predict action unfolding in videos of a child grasping an apple or glass for individual (eating/drinking) or interpersonal (giving) actions. Contextual cues were provided through dish and tablecloth colours, and the amount of cues determined whether the conditions were moderately or highly informative. When participants received sham stimulation, performance was significantly lower for moderately informative contexts compared to highly informative ones. In turn, during anodal stimulation action prediction levels were similar under both moderately and highly informative conditions.

Therefore, a single session of anodal stimulation has been shown to significantly improve participants' ability to predict actions in moderately informative contexts, suggesting that the effects of tDCS are likely mediated by the cerebellar network level of activation, depending on the predictability of the context. In sum, this study underscores the potential of stimulating the cerebellum using tDCS to enhance social predictive abilities in individuals with cerebellar impairments, for improving socio-cognitive functions. Still, further investigations are needed to understand the long-term effects on CM population and to elucidate if such intervention would work similarly for other cerebellar pathologies.

## 5. General conclusion

Herein, we present a review of tDCS as a tool for modulating procedural learning. Studies using alternative neuromodulation techniques such as tACS and TMS have only been superficially explored. While the review's primary focus is on tDCS, it's worth noting that tACS and TMS have also garnered attention for their potential in modulating procedural learning processes (e.g., Mosbacher et al., 2021; Szűcs-Bencze et al., 2023). Further exploration of their effects on procedural learning could offer complementary insights into the neural mechanisms underlying skill acquisition and retention.

Nevertheless, tDCS has been widely used in implicit motor and non-motor learning studies and as a rehabilitation tool. The majority of studies approached motor-procedural learning. By combining the findings of those, stimulation over M1 seems the most promising for boosting both the initial learning and retention phases, whereas targeting the ipsilateral cerebellum, the PPC, and frontal areas have been less studied, and albeit seem to contribute to the retention phase to some extent, for now, there are few studies, and specific benefits remain unclear. Concerning non-motor procedural learning, the employed tasks are mostly related to implicit association and implicit memory. In this regard, the stimulation of prefrontal areas has been shown to benefit acquisition and retention learning phases that may vary in robustness according to the applied current density. The cerebellum, crucial for coordinating predictive computations, plays a key role in both motor and non-motor implicit learning. Although studies on cerebellar stimulation for these tasks are limited, the results seem promising. Thus, making the cerebellum a particularly interesting target for neuro-rehabilitation in the context of procedural tasks, warranting deeper investigation.

Finally, investigations on the use of tDCS for procedural rehabilitation are yet in their early stages and have shown some effectiveness for implicit motor and memory learning in MD, psychosis, PD, and cerebellar malformation. It is important to highlight that for both healthy and clinical samples, some studies have shown contradictory results, leaving open questions about the magnitude of tDCS effects. This is likely in great part related to the lack of consistency between the different studies, most notably concerning target areas, current intensity, electrode size, and stimulation time but also sample sizes and that different tasks are applied, making it more complex to compare and evaluate the specificity of the modulatory effects. Therefore, future studies must make systematic comparisons of the different stimulation

parameters in particular electrode montages, the density of the current, and target areas for the advancement of the technique and to maximize its potential in procedural rehabilitation.

## CRedit authorship contribution statement

**Olivia Morgan Lapenta:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Gabriel Gaudencio Régo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Paulo Sérgio Boggio:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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