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Combining transcranial direct current stimulation with a rhythm-based intervention to improve reading fluency in young adults with dyslexia

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ABSTRACT

Recent evidence suggests that reading performance can be enhanced through non-invasive brain stimulation, which modulates excitability in brain regions involved in reading. However, no studies have tested a multi-session protocol combining tDCS with reading training in adults with developmental dyslexia. The present study investigated the efficacy of combining transcranial direct current stimulation (tDCS) with a behavioral intervention – Rhythmic Reading Training (RRT) – to improve reading skills in university students with dyslexia. Twenty participants (aged 19–26) diagnosed with dyslexia completed a 10-day intervention comprising daily 30-minute sessions of RRT and 15 min of concurrent online tDCS. A constant current of 1.5 mA was applied for 20 min in a bipolar montage with the anode over the left temporoparietal junction (TPJ) and the cathode over the right TPJ. Participants were randomly assigned to either an active or sham tDCS condition, matched for socio-demographic characteristics, intellectual functioning, and severity of reading difficulties. Reading performance, verbal working memory, rapid automatized naming (RAN), and rhythm perception were assessed at baseline (pre-training), immediately after the intervention (post-training), and at a 4-week follow-up. Results showed that the behavioral intervention alone was sufficient to engage phonological processing, as evidenced by significant improvements in nonword reading speed in both the active and sham groups. Additionally, tDCS produced sustained gains in the most ecologically valid measure of reading, namely, text reading speed. These findings indicate that a short, intensive RRT program effectively improves reading speed in university students with dyslexia and that combining RRT with active tDCS over the left temporoparietal cortex may enhance the durability of text reading speed gains through brain plasticity mechanisms.

1. Introduction

Developmental dyslexia is a lifelong neurodevelopmental disorder and its core symptom of impaired reading persists into adulthood (Everatt, 1997; Flowers, 1995; Nergård-Nilssen & Hulme, 2014). Dyslexia involves multifactorial cognitive deficits (Menghini et al., 2010), including impairments in phonological awareness, rapid automatized naming, and verbal working memory (Carioti et al., 2021). However, in adults, symptoms tend to be more pronounced in reading skills than in reading-associated processes, as shown in a *meta*-analysis by Reis et al. (2020). More precisely, dyslexia in adulthood primarily affects reading fluency rather than accuracy, with speed deficits emerging as a consistent marker across orthographies, whereas decoding errors are more common in opaque languages (Reis et al., 2020). Indeed, in transparent orthographies fluency deficits are particularly pronounced compared to accuracy deficits (Cancer & Antonietti, 2018a; Morlini et al., 2014). Overall, while reading accuracy tends to improve with age due to compensatory mechanisms (Carioti et al., 2021; Eloranta et al., 2019), reading speed remains a stable behavioral indicator of dyslexia (Reis et al., 2020).

The persistence of reading fluency impairments in adults with dyslexia can have a substantial impact on study skills and academic performance, highlighting the need for targeted support to enable success in higher education. One approach is the implementation of effective literacy interventions aimed at improving reading skills in adulthood. A systematic review by Vender et al. (2022) reported substantial gains following specialized reading training. These improvements are paralleled by notable neuroplastic changes, as shown by fMRI

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evidence from Eden et al. (2004), who observed increased activation in the left-lateralized reading network typically engaged by skilled readers. Similarly, ERP studies by Shiran and Breznitz (2011) and Horowitz-Kraus (2016) found enhanced reading fluency accompanied by significant electrophysiological changes, suggesting that the plasticity of the adult brain may be greater than previously assumed.

Given this capacity for neural adaptation, non-invasive brain stimulation (NIBS) techniques may offer a promising approach to improving reading outcomes in adults with dyslexia. Neuromodulatory remedial interventions for dyslexia (Krause & Cohen Kadosh, 2013; Vicario & Nitsche, 2013) aimed to use anodal stimulation to target brain areas that are typically underactivated in individuals with dyslexia. This underactivation is frequently observed in the left temporo-parietal region (Maisog et al., 2008; Paulesu et al., 2014; Pugh et al., 2000; Richlan, 2012; Richlan et al., 2011; Turker & Hartwigsen, 2022), a key area for phonological decoding.

Recently, evidence has shown that both children and adults with dyslexia benefit from NIBS, in particular transcranial direct current stimulation (tDCS) (Cancer & Antonietti, 2018b; Naghavi et al., 2025; Salehinejad et al., 2022; Turker & Hartwigsen, 2022). In tDCS, weak direct currents of 1 to 2 mA are applied for up to 20 min through electrodes placed on the scalp (Nitsche & Paulus, 2000). This current alters the resting membrane potential, changing the response threshold of stimulated neurons (Fertonani & Miniussi, 2017). Such modulation can lead to long-lasting cognitive effects (Zaghi et al., 2010) through neuroplastic after-effects involving GABAergic and glutamatergic activity (Stagg & Nitsche, 2011).

Several studies have examined the effect of tDCS targeting the temporo-parietal region on the reading performance of children and adults with dyslexia, using either a single session of tDCS or multiple sessions, applied alone or in combination with cognitive training. Although, as in all neuromodulatory research, possible publication bias should be considered, cumulative findings suggest a modulatory effect of tDCS on reading processes. The first study testing tDCS on reading, conducted by Turkeltaub et al. (2012), found that a single session of stand-alone bilateral tDCS over the temporo-parietal junction (TPJ), with left anodal and right cathodal stimulation, improved word reading efficiency in healthy adults with below-average reading skills. Using the same tDCS montage, Costanzo et al. (2016b) tested children and adolescents aged 10 to 17, reporting improvements in text reading accuracy. Extending these findings, Lazzaro et al. (2021) confirmed that left anodal/right cathodal tDCS over TPJ improved text reading accuracy, but also word recognition speed, motion perception, and visual attention in children and adolescents with dyslexia. Targeting a more superior portion of the left temporo-parietal cortex (P3), based on its role in fine-grained grapheme-to-phoneme mapping and early reading network development (Pugh et al., 2000), Younger et al. (2016) found that anodal tDCS over the left inferior parietal lobe improved word reading efficiency in below average reading adults.

Notably, repeated tDCS sessions produce greater improvements in learning task performance and longer-lasting effects than a single session, likely by long-term potentiation-like neuroplasticity (Berryhill & Martin, 2018; Hashemirad et al., 2016). Accordingly, other tDCS studies have employed multiple sessions of stand-alone stimulation in an attempt to achieve stronger and more lasting effects. Battisti et al. (2022) applied five consecutive daily sessions of left anodal/right cathodal tDCS over parieto-occipital regions (PO7, PO8) in children and adolescents with dyslexia aged 10 to 18 and found improvements in nonword reading speed immediately after treatment and one month later. In another multi-session stand-alone intervention, Rios et al. (2018) applied tDCS for five consecutive days in children and adolescents with dyslexia aged 8 to 17, with left anodal stimulation midway between T3 and T5 and the cathode over the right supraorbital region (FP2). The study reported a significant increase in correct responses for nonword and text reading tasks, although the absence of a control group warrants caution in interpreting these results. More recently, Rezaei et al. (2025) applied twelve 20-minute sessions of left anodal/right cathodal tDCS over TPJ in children with dyslexia aged 9 to 12. This intervention significantly improved low-frequency and nonword reading, as well as text reading errors, immediately and one month after treatment, while high-frequency and irregular word reading showed no significant changes.

Most studies used bipolar montages with the cathode over the right temporoparietal cortex, based on evidence that children with dyslexia show reduced right temporal activation after successful reading interventions and greater activation when interventions fail (Odegard et al., 2008; Shaywitz et al., 2004). This supports the efficacy of left anodal/right cathodal tDCS in improving reading in dyslexia. However, findings from two studies using single-session unipolar montages (Cummine et al., 2020; Rahimi et al., 2019), despite showing mixed results, challenged the notion that bipolar montages are inherently optimal for reading improvement in dyslexia. Cummine et al. (2020) found minimal effects of P3 anodal tDCS with the cathode on the right arm in adults with dyslexia, whereas Rahimi (2019) reported improvements in reading accuracy and speed in children with dyslexia (mean age 10) using both unipolar and bilateral bipolar montages, with no significant difference between the two.

Although promising, the effects of standalone tDCS for remediation in clinical populations may be limited. Indeed, longitudinal protocols that pair stimulation with concurrent cognitive tasks are considered optimal for achieving stronger and longer-lasting cognitive effects (Berryhill & Martin, 2018). Combining tDCS with behavioral reading interventions appears particularly effective to treat dyslexia (Cancer & Antonietti, 2018b; Finisguerra et al., 2019), as engagement in a task during stimulation directs the neuromodulatory effects to relevant neural circuits. Because tDCS modulates resting membrane potentials in a subthreshold manner, concurrent brain activity is required to induce lasting neuroplastic changes (Fritsch et al., 2010). Repeated sessions of such combined interventions may further enhance task-related improvements through long-term potentiation-like mechanisms, resulting in more durable gains in reading performance.

Costanzo et al. (2016a) conducted the first study combining active tDCS over the TPJ with a cognitive intervention in children and adolescents with dyslexia (age 10–17). The protocol involved 18 sessions over six weeks, with left anodal/right cathodal tDCS paired with phonemic training, including tachistoscopic verbal stimulus presentation to improve reading speed and phonic training focused on letter-sound rules to improve accuracy. The combined intervention reduced errors in low-frequency word and nonword reading compared to behavioral training alone but showed no significant effects on high-frequency word or text reading accuracy and speed. A follow-up (Costanzo et al., 2019) showed that improvements, particularly in nonword and low-frequency word reading efficiency, were maintained up to six months. A subsequent study using the same protocol (Lazzaro et al., 2020) replicated these reading gains and further highlighted that improvement was modulated by individual factors, with greater benefits for children with lower baseline reading skills, older age, and higher IQ. Finally, Mirahadi et al. (2022) combined left-anodal/right-cathodal TPJ tDCS with a phonological awareness intervention in children with dyslexia (age 7–12) over 15 sessions, three times a week, with tDCS applied during the first 20 min of each 60-minute session. The active tDCS group showed significant improvements in nonword reading and phonological awareness during, immediately after, and six weeks following the intervention compared to the sham group.

Although the specific reading measures affected varied across studies, the accumulated evidence supports the efficacy of left anodal/right cathodal TPJ tDCS in enhancing reading skills in dyslexia (Cancer & Antonietti, 2018b; Naghavi et al., 2025; Salehinejad et al., 2022; Turker & Hartwigsen, 2022). However, studies in adults are limited to single-session investigations (Cummine et al., 2020; Turkeltaub et al., 2012; Younger et al., 2016) and none has tested a repeated-session protocol combined with reading training in adults with dyslexia.

In the present study we aim to address this gap by investigating the effects of a multi-session intervention of tDCS paired with a training aimed at improving reading in adults with dyslexia. The reading intervention employed was a rhythm-based program, Rhythmic Reading Training (RRT, Cancer et al., 2016), which has proven efficacy in younger populations (Bonacina et al., 2015; Cancer et al., 2019, 2020; Cancer, Sarti, et al., 2021; Cancer et al., 2022, 2023; Cancer & Antonietti, 2017). The intervention integrates reading exercises with accelerated rhythm synchronization tasks and is based on the Temporal Sampling Framework (Goswami, 2011; Goswami et al., 2014). This framework links dyslexia to deficits in temporal processing of auditory stimuli caused by atypical neural oscillatory activity, which contribute to phonological and reading difficulties.

1.1. Aims

The aim of the present study was to test the efficacy of an intervention combining tDCS with a rhythm-based intervention for reading, namely, RRT, in university students with dyslexia. Specifically, the study aimed (a) to measure the effect of intensive RRT on reading speed (the primary outcome) across three reading conditions assessed separately – namely, text reading, word reading, and nonword reading – and measured immediately after training and at a four week follow up, controlling for baseline severity of reading impairment; (b) to evaluate the effect of bilateral tDCS over TPJ (left anodal/right cathodal), compared with sham stimulation, on the same reading measures to assess the specific contribution of neuromodulation; and (c) to examine the interaction between RRT and tDCS to determine whether active stimulation enhances immediate improvements and supports their maintenance at follow-up. Secondary outcome measures included verbal working memory, RAN, and rhythm discrimination, which were analyzed using the same approach as the primary outcomes.

2. Methods

2.1. Participants

A power analysis conducted with G*Power version 3.1.9.6 (Faul et al., 2007) indicated that a total sample of 20 participants was required to detect a medium effect size (Cohen's d = 0.6) for a 3 × 2 mixed ANOVA, with 80% power and an alpha level of 0.05. Twenty Italian university students (11 females), aged 19–27 years, with a formal diagnosis of developmental dyslexia participated in the study. Recruitment was conducted through the Learning Disability Services of three universities in Milan, Italy.

Inclusion criteria were: (a) current enrollment in a university course; participants were also required to be at least 18 years old; (b) a prior diagnosis of developmental dyslexia (ICD-10 code F81.0) based on the standard diagnostic procedures (ICD-10: World Health Organization, 1992) and inclusion/exclusion criteria adopted in Italy (PARCC., 2011); (c) absence of comorbidity with other neuropsychiatric or psychopathological disorders (comorbidity with other learning disabilities was permitted); (d) right-handedness; (e) no participation in specific reading programs within the past 12 months. Exclusion criteria included current use of central nervous system-active medication, pregnancy, a history of seizures or epilepsy, severe headaches, and the presence of metallic, electrically sensitive, or mechanically implanted devices. Participants were matched on age, gender, year of university study, field of study, intellectual functioning (with total IQ derived from diagnostic reports), musical expertise (self-reported attendance to music courses), and baseline reading impairment and then assigned to either the active (n = 11) or sham (n = 9) tDCS group; the unequal group sizes reflect the outcome of the matching process.

2.2. Reading intervention

RRT (Cancer et al., 2016) is a computerized program aimed at improving reading in individuals with dyslexia by embedding specific reading tasks within an isochronous rhythm. Based on the Temporal Sampling framework (Goswami, 2011; Goswami et al., 2014) and evidence supporting the effectiveness of rhythm-based interventions for dyslexia (for a review, Cancer & Antonietti, 2022), RRT was developed to integrate regular beat synchronization into reading activities in order to improve temporal processing and support the segmentation of hierarchical rhythmic patterns in language by highlighting temporal acoustic cues associated with phonological units. The program consists of syllable, word, nonword, and text reading exercises of increasing difficulty, with personalized settings enabling the trainer to adjust tasks to the participant's abilities. The rhythm tempo is modified according to performance and gradually increased. Advancement to the next exercise requires at least 95% reading accuracy for the verbal stimuli. Controlled studies have shown positive effects of RRT on reading speed and accuracy in children with dyslexia aged 8–13 years (Bonacina et al., 2015; Cancer et al., 2019, 2020; Cancer, Sarti, et al., 2021; Cancer et al., 2022, 2023; Cancer & Antonietti, 2017).

2.3. tDCS parameters

Direct current was generated by HDC Series stimulator by Newronika (S.r.l., Milan) and delivered by a pair of two 5x5cm (25 cm^2 each) rubber electrodes enveloped in saline-soaked sponges covered with conductive gel. The anodal electrode was positioned over the participants' left TPJ, on the area corresponding midway between P7 and TP7, according to the 10–20 EEG international system (Fig. 1).

The cathodal electrode was positioned over the homologue ipsilateral region (right TPJ, midway between P8 and TP8). This specific setup (left anodal/right cathodal over TPJ) has shown to be effective in modulating reading performance in previous tDCS studies (Battisti et al., 2022; Costanzo et al., 2016a, 2016b, 2019; Lazzaro, Bertoni, et al., 2021; Lazzaro, Costanzo, et al., 2021; Mirahadi et al., 2022; Rezaei et al., 2025; Younger et al., 2016). The left area was stimulated at a constant current of 1.5 mA for 20 min, resulting in a current density of 0.06 mA/cm^2. At the beginning of stimulation the current was gradually increased (ramp-up) in 7 proportional intervals during the first 7 s to the stimulation threshold. Stimulation was initiated 5 min before the beginning of RRT. RRT exercises were delivered for 30 min and presented

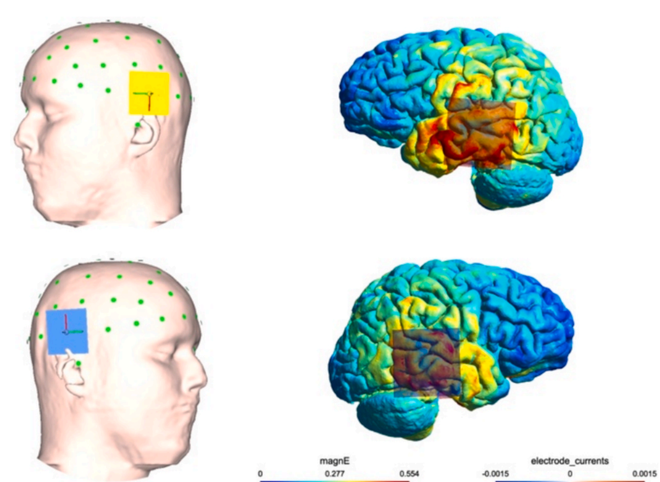

Fig. 1. tDCS setup with anode (upper section, yellow) over left TPJ and cathode (lower section, blue) over right TPJ and the simulated magnitude of the electric field distribution (SimNIBS 4.5.0; Thielscher et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

simultaneously with the stimulation for the initial 15 min. This timing was selected based on three main methodological aspects. First, concurrent stimulation can be more efficient than pre-training-only stimulation (Kwon et al., 2013; Stagg et al., 2011), since it interacts with ongoing task-evoked neural activity, thus facilitating task-evoked plastic changes. Second, a brief pre-task stimulation period (up to 5 min) can enhance task-related effects (Fregni et al., 2005; Heinen et al., 2016). Finally, the protocol was designed to be comparable to other relevant studies in the field to promote generalizability.

2.4. Procedure

After providing informed consent, participants were screened for inclusion and exclusion criteria through an analysis of their clinical history and diagnostic report. Enrolled participants took part in a single-blind, sham-controlled design study comparing active and sham tDCS conditions. They completed a brief, intensive intervention comprising 10 individual RRT sessions over two weeks, conducted in a university laboratory and supervised by a specialized trainer. Each session started with 5 min of tDCS only, then continued with 30 min of RRT, with tDCS delivered concurrently during the first 15 min.

All participants attended all 10 individual RRT sessions and completed three assessment sessions – pre-intervention, post-intervention, and a 4-week follow-up – administered by an examiner specialized in neuropsychological assessment to evaluate reading and secondary outcome measures including verbal working memory, RAN, and rhythm discrimination. To ensure experimental blinding, both the examiner and the RRT trainer were blinded to participants' condition assignment. Furthermore, to monitor tDCS tolerability and evaluate the effectiveness of participant blinding, stimulation-related sensations were assessed after each session.

The study was approved by the Ethics Committee of the Università Cattolica del Sacro Cuore of Milan, Italy, and was pre-registered on ClinicalTrials.gov (ID: NCT03119402). The entire research process was conducted according to the standards of Helsinki Declaration (World Medical Association., 2001).

2.5. Assessment

To evaluate the effect of the intervention on the primary outcome measure, reading speed, participants completed three reading tasks: text reading, word reading, and nonword reading. Secondary outcome measures, assessing cognitive functions involved in reading, included rapid automatized naming (RAN), verbal working memory (backward digit span), and rhythm perception abilities (rhythm discrimination).

Text reading. Text reading ability was measured using the Text Reading Test for Secondary School (Judica and De Luca, 2005), which assesses aloud reading of prose passages. Two passages ("Funghi in città" [Mushrooms in town] and "Viaggio con le mucche" [A trip with the cows]) were used and scores for accuracy (errors per word) and speed (syllables per second) were averaged separately to obtain composite measures of speed and accuracy.

Word and nonword reading. Word and nonword reading were assessed with the Word Reading and Nonword Reading subtests from the DDE-2 Battery for the Evaluation of Developmental Dyslexia and Dysorthographia (Sartori and Job, 2007). The word reading task included four lists of words varying in length, frequency, and concreteness, while the nonword reading task included three lists of pseudo-words varying in length and difficulty. For both tasks, speed (syllables per second) and accuracy (errors per word) were calculated.

Working memory. Verbal working memory was assessed using the Backward Digit Span subtest (Wechsler, 2008), with scores corresponding to the number of correct items.

Rapid Automatized Naming (RAN). RAN was measured with the "Colors" and "Objects" subtests of the Rapid Automatized Naming Battery (De Luca et al., 2005). In the Colors subtest participants named items of two matrices of 10 rows × 5 colored squares (black, blue, red, yellow, green). In the Objects subtest they named items of two matrices of 10 rows × 5 black-and-white line drawings (pear, train, dog, star, hand). For both subtests participants named stimuli sequentially as quickly and accurately as possible and naming speed (in seconds) was recorded. These RAN subtests were selected based on prior evidence indicating that color and object RAN speed strongly predicted reading performance and dyslexia risk in Italian adults (Cancer & Antonietti, 2018a).

Rhythm perception. Rhythm discrimination was assessed with an ad hoc same-different judgment task adapted from the procedure described in Wallentin et al. (2010). In 20 trials, participants heard pairs of pre-recorded drum patterns composed of same-pitch notes in a 5/4 time signature. After each pair, they judged whether the two rhythms were the same or different. Scores were the number of incorrect responses.

tDCS tolerability. tDCS-related sensations at the electrode site were assessed using a standard questionnaire (Fertonani et al., 2010) that includes symptoms such as irritation, pain, burning, heat, itching.

2.6. Analyses

First, to verify the matching procedure, we compared sociodemographic characteristics (age, gender, year of university study, field of study), intellectual functioning, musical expertise, and baseline reading abilities (pre-training reading speed composite score calculated as the mean syllables per second for word, nonword, and text reading; pre-training reading accuracy composite score calculated as the mean errors per word for word, nonword, and text reading) between the active tDCS and sham groups. Welch's *t*-test was used for continuous variables and the chi-squared test for categorical variables.

To evaluate whether blinding to stimulation condition was successful, mean ratings of tDCS-related sensations (irritation, pain, burning, heat, itching) across the 10 sessions were compared between the active and sham groups using Welch's t-tests.

Subsequently, to test the effect of the combined tDCS and RRT intervention on the primary outcome, mixed factorial GLMs were conducted separately for text, word, and nonword reading speed, with time (pre, post, follow-up) as the within-subject factor and group (active tDCS, sham) as the between-subject factor.

Based on prior evidence indicating that the effects of combined tDCS and reading training on reading fluency vary according to baseline reading level (Lazzaro et al., 2020), pre-training reading accuracy – calculated as the composite score of mean errors per word for word, nonword, and text reading – was included as a covariate to control for baseline reading impairment severity. This measure was independent of those entered as dependent variables in the models.

Finally, the same mixed factorial GLMs were conducted separately for each of the three secondary outcome measures (verbal working memory, RAN, rhythm discrimination), with phase (pre, post, follow-up) as the within-subject factor and group (active tDCS, sham) as the between-subject factor.

Post-hoc pairwise comparisons were computed using Tukey's test. Partial eta squared ($\eta^2 p$) was reported as the effect size measure, following recommendations for factorial designs (Richardson, 2011).

3. Results

To verify the matching procedure, sociodemographic characteristics, intellectual functioning, and baseline reading abilities were compared between the active tDCS and sham groups. No significant differences were found between groups on any of these measures, indicating comparable baseline characteristics (see Table 1).

Regarding tDCS tolerability, no participant reported significant discomfort during or after stimulation. Comparisons of mean ratings for tDCS-related sensations (irritation, pain, burning, heat, and itching) revealed no significant differences between the active and sham groups

Table 1
Participants' characteristics and comparisons between groups.

	Active tDCS (n = 11) Mean (SD)	Sham (n = 9) Mean (SD)	*t*	*p*-value
Age	22.36 (2.42)	21.20 (1.92)	1.19	0.25
Year of university study	2.82 (1.47)	2.11 (1.17)	1.20	0.25
TIQ	111.81 (14.55)	107.67 (8.21)	0.75	0.46
Baseline reading speed (syll/sec)	3.12 (0.93)	3.35 (0.88)	0.38	0.71
Baseline reading accuracy (err/word)	0.05 (0.03)	0.04 (0.03)	0.41	0.69
tDCS tolerability				
Irritation	1.32 (1.06)	0.82 (2.32)	0.63	0.53
Pain	0.29 (0.80)	0.00 (0.00)	1.08	0.29
Burning	0.57 (1.06)	0.55 (1.67)	0.03	0.98
Heat	0.34 (0.76)	0.54 (1.32)	0.42	0.68
Itching	1.22 (0.94)	1.10 (2.23)	0.16	0.87
	n	n	χ^2	*p*-value
Sex				
Female	5	6	0.90	0.34
Male	6	3		
Field of study				
Humanities	4	3	0.20	0.88
Sciences	7	6		
Musical expertise				
Yes	6	5	0.002	0.96
No	5	4		

(see Table 1). These findings indicate that participants were unable to distinguish between stimulation conditions, confirming that blinding was successful.

The analysis of text reading speed showed a significant main effect of phase ($F(2,34) = 13.03$, $p < 0.001$, $\eta_p^2 = 0.43$), indicating that all participants improved overall across the three time points (pre, post, follow-up). Additionally, there was a significant interaction between phase and condition (active tDCS vs. sham) ($F(2,34) = 4.69$, $p = 0.02$, $\eta_p^2 = 0.19$), suggesting that the pattern of improvement differed between the active tDCS and sham groups. Post-hoc pairwise comparisons revealed that both groups showed significant text reading speed improvements from pre- to post-training (active tDCS: $p = 0.04$; sham: $p = 0.001$). However, at the 4-week follow-up, only the active tDCS group maintained significant gains compared to baseline ($p = 0.005$), while the sham group's performance no longer differed significantly from baseline ($p = 0.57$).

For word reading speed, although the main effect of phase reached significance ($F(2,34) = 5.82$, $p = 0.007$, $\eta_p^2 = 0.25$), pairwise post-hoc comparisons did not reveal significant differences between pre- and post-training or between pre-training and follow-up, and the phase-by-group interaction was not significant ($F(2,34) = 0.24$, $p = 0.40$, $\eta_p^2 = 0.05$).

For nonword reading speed, a significant main effect of phase emerged ($F(2,34) = 15.26$, $p < 0.001$, $\eta_p^2 = 0.47$), with post-hoc comparisons indicating improvements from pre- to post-training ($p < 0.001$) and from pre-training to follow-up ($p < 0.001$) and no significant interaction between phase and group ($F(2,34) = 0.64$, $p = 0.53$, $\eta_p^2 = 0.04$). Fig. 2 shows the improvements in reading speed across assessment phases for both groups.

As for the secondary outcome measures, verbal working memory and rhythm discrimination showed no significant main effects of phase or interactions (verbal working memory: phase $F(2,34) = 0.79$, $p = 0.46$, $\eta_p^2 = 0.04$; interaction $F(2,34) = 0.09$, $p = 0.91$, $\eta_p^2 = 0.005$; rhythm discrimination: phase $F(2,34) = 0.58$, $p = 0.56$, $\eta_p^2 = 0.03$; interaction $F(2,34) = 1.96$, $p = 0.16$, $\eta_p^2 = 0.10$). In contrast, RAN speed showed a significant main effect of phase ($F(2,34) = 3.32$, $p = 0.04$, $\eta_p^2 = 0.16$) but no significant interaction ($F(2,34) = 0.44$, $p = 0.65$, $\eta_p^2 = 0.02$). Descriptive statistics for all measures are reported in Table 2.

Table 2
Descriptive statistics for all measures by group at pre, post, and follow-up assessments.

		Active tDCS (n = 11) Mean (SD)	Sham (n = 9) Mean (SD)
Text reading speed (syll/sec)	pre	3.81 (1.11)	3.82 (0.85)
	post	4.22 (1.05)	4.57 (1.00)
	follow-up	4.53 (1.03)	4.19 (0.44)
Word reading speed (syll/sec)	pre	3.79 (1.10)	4.08 (1.33)
	post	4.25 (0.90)	4.20 (1.09)
	follow-up	4.37 (0.71)	4.36 (0.73)
Nonword reading speed (syll/sec)	pre	1.99 (0.69)	2.15 (0.59)
	post	2.55 (0.70)	2.53 (0.54)
	follow-up	2.62 (0.78)	2.75 (0.33)
Verbal working memory	pre	5.91 (1.22)	6.11 (1.27)
	post	6.45 (1.37)	6.89 (1.69)
	follow-up	6.64 (2.29)	6.78 (1.72)
RAN (sec)	pre	64.00 (10.69)	66.67 (7.45)
	post	59.50 (10.52)	58.56 (5.78)
	follow-up	59.95 (13.54)	61.28 (8.36)
Rhythm discrimination (errors)	pre	5.91 (2.51)	3.11 (2.89)
	post	4.82 (2.23)	3.00 (2.18)
	follow-up	5.00 (2.83)	4.11 (3.72)

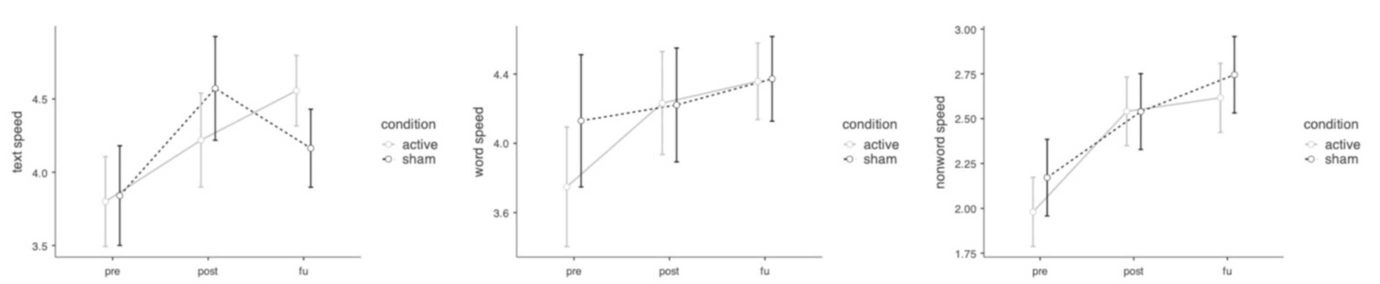

Fig. 2. Reading speed improvements across assessment phases (pre, post, follow-up) for the active tDCS and sham groups. Error bars indicate standard error of the mean.

4. Discussion

This is the first study which tested the effects of a multi-session combined intervention of tDCS paired with behavioral training to improve reading in adults with dyslexia. Our findings revealed that the intensive application of RRT intervention in university students with dyslexia led to significant improvements in nonword reading speed for all participants, thus suggesting that the rhythmic intervention, in line with its theoretical foundations (Goswami, 2011), engaged phonological processing mechanisms and enhanced grapheme-phoneme conversion. Notably, only participants who received active tDCS sustained their gains at the 4-week follow-up on text reading speed, a naturalistic and complex measure of reading and the most critical outcome for adult reading rehabilitation, indicating a lasting benefit of neuromodulation when combined with behavioral training. Converging evidence indicates that tDCS can enhance the behavioral effects of cognitive training alone (e.g., Pergher et al., 2022). For example, when considering reading abilities in children, they proved to be even more facilitated when the reading training was accompanied by active vs. sham tDCS (Costanzo et al., 2019; Mirahadi et al., 2022). The present study is the first one replicating this finding within a combined protocol in adults with dyslexia. Still, the benefits of tDCS stimulation are cumulative, especially when paired with cognitive training, and repeated sessions are necessary to shift from transient excitability changes to enduring plasticity (Besson et al., 2016; Senkowski et al., 2022).

Most previous research on tDCS in dyslexia had focused on children, under the assumption that applying tDCS during developmental age may be particularly promising because language-related circuits are thought to exhibit greater plasticity in childhood compared to adulthood (Andrade et al., 2014). However, investigating tDCS effect on adults with dyslexia is particularly relevant for three main reasons. (1) Most studies conducted on children and adolescents included participants across a very wide age range – up to 17 years old (e.g., Battisti et al., 2022; Costanzo et al., 2016a, 2016b, 2019; Lazzaro, Bertoni, et al., 2021, 2021; Lazzaro, Costanzo, et al., 2021; Rios et al., 2018), which introduces substantial variability in both reading development and responsiveness to intervention that do not allow to separate results from a developing vs. mature neurofunctional systems. (2) Adult brains can, and do, still change in response to treatment (Figeys et al., 2021; Narmashiri & Akbari, 2023) and in dyslexia (Cancer & Antonietti, 2018b; Naghavi et al., 2025; Salehinejad et al., 2022; Turker & Hartwigsen, 2022). (3) Although repeated tDCS applications can be tolerated by children and adolescents, without significant discomfort or adverse effects (Andrade et al., 2014; Costanzo et al., 2019; Lazzaro, Costanzo, et al., 2021; Mirahadi et al., 2022; Rahimi et al., 2019, p. 20; Rios et al., 2018) up to 6 months after the end of the intervention (Costanzo et al., 2019), tDCS in pediatric population is associated with ethical concerns (Cancer, Santi, et al., 2021). Indeed, still limited evidence exists about a potential maladaptive long-term effect on plasticity (Riggall et al., 2015).

In our study, tDCS induced significant improvement in text reading, but no specific effects were found for word and nonword reading speed. This finding adds to the heterogeneous literature on the effects of tDCS on reading, in which similar left anodal/right cathodal montages have been associated with different outcomes, ranging from word, low-frequency word, and nonword reading to text fluency and accuracy (Cancer & Antonietti, 2018b; Costanzo et al., 2016a, 2016b, 2019; Turkeltaub et al., 2012; Younger et al., 2016). Previous research suggested that improvements in word and text reading are more likely when stimulation targets the medium and inferior temporal gyri, regions specifically involved in word recognition (Costanzo et al., 2016a; Dehaene et al., 2005; Vinckier et al., 2007), whereas temporo-parietal dysfunctions in adults with dyslexia are typically associated with phonological tasks such as nonword reading (Richlan et al., 2011).

However, given that other studies using similar montages did find changes in word reading (Turkeltaub et al., 2012; Younger et al., 2016), the apparent inconsistency may not be fully explained by electrode placement alone. It is therefore plausible that variations in the number of sessions (10 vs. 1) and the inclusion of cognitive training specifically targeting reading processes account for the heterogeneous outcomes observed across studies. In our case, text reading, being the most ecological task, requires the integration of multiple linguistic and cognitive processes, thereby recruiting a broader neural network that might be more sensitive to neuromodulation. The cognitive component of our combined training appears to specifically target phonological processes, as reflected in improvements in nonword reading that occurred independently of tDCS. The lasting modulation of the more complex and naturalistic measure of reading speed, however, was only maintained over time when tDCS induced plasticity in the left TPJ, consistent with evidence from a study in adults with developmental dyslexia showing that an intensive phonology-based intervention increased activation in the left inferior parietal lobule and intraparietal sulcus and led to improvements in both nonword and text reading, demonstrating that enhanced phonological processing can generalize to broader aspects of reading ability (Eden et al., 2004).

Finally, secondary outcomes showed improvement over time only in RAN speed thanks to RRT but not to tDCS, while verbal working memory and rhythm discrimination remained unchanged. RAN is one of the main cognitive deficits underlying developmental dyslexia and is strongly related to reading fluency, even in adult samples (Araújo & Faísca, 2019; Cancer & Antonietti, 2018a; Nergård-Nilssen & Hulme, 2014). RAN has been described as supporting orthographic processing, in that it reflects the ability to process groups of letters or entire words as whole lexical units rather than through a sequence of grapheme-phoneme correspondences (Georgiou et al., 2009). In line with this view, the present results suggest that the effects of RRT on reading may be associated with enhancements in auditory temporal processing (Cancer et al., 2022), which could contribute to the observed gains in RAN. This finding replicates previous evidence in children (Cancer, Sarti, et al., 2021). However, although RRT improved multiple reading measures, this finding should be interpreted with caution because both groups received the same behavioral intervention, and no passive or active control condition was included in the study design.

Despite the positive impact of RRT on reading fluency and RAN, no significant effects were found on verbal working memory and rhythm discrimination. This result is not surprising and reflects what has been already revealed by previous investigation in adolescents (Bonacina et al., 2015). Thus, it has been hypothesized that RRT can bolster reading by enforcing temporal structure without necessarily enhancing the perceptual discriminative ability of rhythm itself. Moreover, another study (Cancer et al., 2019) found that baseline verbal working memory and rhythm discrimination were negatively correlated with improvements in reading speed via RRT in a sample of children with dyslexia. This suggests these variables as predictors or moderators of RRT's efficacy but not as direct targets of RRT.

5. Conclusions

The present study provides novel insights into the potential of combining RRT with non-invasive brain stimulation in university students with developmental dyslexia. Our findings confirm that RRT was effective in improving reading performance in phonological-based tasks, independently of concurrent tDCS.

Also, while the short-term benefits of RRT were not differentially influenced by stimulation, the medium-term effects on text reading were selectively enhanced by active tDCS. This result is particularly promising since text reading can be considered the most ecological measure of reading proficiency and our training could provide concrete, tangible improvements in university students' everyday reading, with possible positive outcomes on academic proficiency and psychological well-being.

Finally, the present evidence indicates that the combination of RRT with anodal tDCS over the left TPJ may represent a promising approach to maximize the efficacy of behavioral training in dyslexia, with specific benefits for text reading. This finding provides new insights into the importance of integrating targeted cognitive interventions with neuromodulatory techniques to enhance and sustain reading fluency in dyslexia.

However, the study is not without limitations. First, the relatively small sample size reduces the generalizability of the findings and may have amplified the individual differences in reading strategies and compensatory mechanisms; In general, larger samples would be necessary to more reliably estimate the size and robustness of tDCS-related effects. Second, participants' musical experience was assessed only via a binary self-report measure, limiting our ability to characterize the extent and potential moderating role of different levels of prior musical training; However, prior work in adolescents with dyslexia found that formal musical training did not modulate responsiveness to RRT (Cancer & Antonietti, 2017). Third, the absence of an active behavioral control intervention precludes more solid conclusions about the specificity of RRT-related improvements in adults. Fourth, we targeted only a single stimulation site (TPJ), which does not allow us to determine whether alternative montages might produce differential effects on distinct reading sub-processes. In addition, we did not specifically control for variability in prior reading interventions received during childhood, beyond excluding participants who had engaged in specific reading programs within the 12 months preceding enrollment. Although prior educational and therapeutic experiences may contribute to individual neurofunctional variability in adulthood, current evidence suggests that core neural markers of dyslexia, such as left temporo-parietal hypoactivation, tend to persist into adulthood and are not reliably normalized by behavioral interventions (Perdue et al., 2022). Accordingly, while childhood interventions may have contributed to inter-individual differences, they are unlikely to have biased the tDCS-related effects observed in the present study. Finally, when interpreting results, it is important to recognize that, besides transcranial effects, transcutaneous mechanisms can also be relevant (Van Boekholdt et al., 2021). In fact, the peripheral field is strong enough to stimulate peripheral nerves (in our specific case, most likely the trigeminal nerve) and consequently the somatosensory and the ascending reticular activating system, with possible effects on arousal and vigilance. Since these effects are not present during the sham treatment, the hypothesis that the effects in the active condition could be, at least in part, attributed to increased vigilance and arousal should be acknowledged and deserves future investigation.

Future development of this work, besides working on larger samples, adding differential control conditions, and using different application sites, may also include the introduction of electrophysiological measures. This integration would allow assessing the potential impact of combined RRT-tDCS treatment on oscillatory neural activity and site localization. In addition, future studies could incorporate pre/post measures of psychological well-being to examine whether the intervention effects extend beyond reading performance to domains such as self-efficacy, which may in turn reinforce and sustain practice-related gains.

6. Declaration of generative AI in the writing process

During the preparation of this work the authors used ChatGPT for linguistic revision. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Alice Cancer: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Elide Vanutelli:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Claudio Lucchiari:** Writing – review & editing, Supervision. **Alessandro Antonietti:** Writing – review & editing, Supervision, Project administration.

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.

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Data availability

Data will be made available on request.

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