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Evidence for reading improvement following tDCS treatment in children and adolescents with Dyslexia

Floriana Costanzo[a], Cristiana Varuzza[a], Serena Rossi[a], Stefano Sdoia[a], Pamela Varvara[a],
Massimiliano Oliveri[b], Koch Giacomo[b], Stefano Vicari[a] and Deny Menghini[a,*]
[a] *Child Neuropsychiatric Unit, Bambino Gesù Children Hospital, Department of Neuroscience, Piazza Sant'Onofrio 4, Rome, Italy*
[b] *Clinical and Behavioral Neurology, Santa Lucia Foundation, Rome, Italy*

Abstract.

Purpose: There is evidence that non-invasive brain stimulation transitorily modulates reading by facilitating the neural pathways underactive in individuals with dyslexia. The study aimed at investigating whether multiple sessions of transcranial direct current stimulation (tDCS) would enhance reading abilities of children and adolescents with dyslexia and whether the effect is long-lasting.

Methods: Eighteen children and adolescents with dyslexia received three 20-minute sessions a week for 6 weeks (18 sessions) of left anodal/right cathodal tDCS set at 1 mA over parieto-temporal regions combined with a cognitive training. The participants were randomly assigned to the active or the sham treatment; reading tasks (text, high and low frequency words, non-words) were used as outcome measures and collected before treatment, after treatment and one month after the end of treatment. The tolerability of tDCS was evaluated.

Results: The active group showed reduced low frequency word reading errors and non-word reading times. These positive effects were stable even one month after the end of treatment. None reported adverse effects.

Conclusions: The study shows preliminary evidence of tDCS feasibility and efficacy in improving non-words and low frequency words reading of children and adolescents with dyslexia and it opens new rehabilitative perspectives for the remediation of dyslexia.

Keywords: Brain stimulation, parieto-temporal regions, cognitive training

1. Introduction

Developmental dyslexia is a persistent difficulty in learning to read, which occurs in 5–17% of children, and it is not explained by sensory deficits, cognitive deficits, lack of motivation, or lack of adequate reading instruction (Ferrer et al., 2010).

Distributed neural systems in the left hemisphere are involved in typical reading: an anterior system, mainly located in the inferior frontal gyrus, and two posterior systems, one in the occipito-temporal region (ventral stream) and one in the parieto-temporal region (dorsal stream) (Price, 2000; Shaywitz et al., 2002; Turkeltaub et al., 2002; Price & Mechelli, 2005; Philipose et al., 2007; Graves et al., 2010). In developmental dyslexia, studies documented hypoactivation of the left dorsal parieto-temporal regions and of the left ventral occipito-temporal regions and overactivation of the left and right inferior frontal regions

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*Corresponding author: Dr. Deny Menghini, Bambino Gesù Children Hospital, Department of Neuroscience, Child Neuropsychiatric Unit, Piazza Sant' Onofrio 4, I-00165 Rome, Italy. Tel.: +39 0668592734; Fax: +39 0668592450; E-mail: deny.menghini@opbg.net.

during reading and reading related-tasks (Shaywitz, 1998; Richlan, 2012). However, the most consistent neuroimaging finding in dyslexia across researches is a left parieto-temporal region reduced activation during phonological processing (Hoeft et al., 2007) and non-word and real word reading (Shaywitz et al., 2002).

To date, only cognitive methods have been adopted for the remediation of dyslexia, supporting that treatment improves reading and modifies activation in critical brain regions (Simos et al., 2002; Aylward et al., 2003; Temple et al., 2003; Eden et al., 2004; Shaywitz et al., 2004). Specifically, successful reading is mediated by a growth of activation in the left parieto-temporal cortex (Hoeft et al., 2011).

Recent progress underlines how some changes in brain functioning itself may be a necessary mechanism of behavioral improvement (Stuss, 2011). Consequently, directly inducing brain change could lead to positive effects in performance. The use of non-invasive brain stimulation offers the possibility to induce excitability alterations in different cortical regions and it may result in positive modulation of performance, providing the opportunity to go above, and even beyond traditional cognitive treatment. Moreover, it has been suggested that transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) protocols should be developed as remediation tools to enhance cognitive functions in specific learning disability (Frye et al., 2008; Krause & Cohen Kadosh, 2013; Vicario & Nitsche, 2013). Studies with high frequency repetitive TMS in adults (Costanzo et al., 2012, 2013) demonstrated evidence that a facilitation of neural pathways underactive in individuals with dyslexia transitorily modulates reading performance of expert readers and adults with dyslexia, improving in both groups non-word reading after the stimulation of the left inferior parietal lobe and, in individuals with dyslexia, text and word reading after the stimulation of the left superior temporal gyrus. Moreover, an important step for the application of tDCS to rehabilitative purpose in developmental learning disabilities is represented by results which documented reading speed improvement after anodal tDCS over the left visual extrastriate region MT/V5 in adults with dyslexia (Heth & Lavidor, 2015) and increased numerical proficiency after anodal tDCS over the left posterior parietal cortex in adults with dyscalculia (Iuculano & Cohen Kadosh, 2014).

To date, no study evaluating the efficacy of tDCS in improving reading abilities of young populations with dyslexia has been conducted yet. However, it is critical to remediate reading problems especially during developmental ages considering that, if left unremediated, learning disabilities continues to hinder the retention of literacy skills, occupational endeavors, and other functional everyday life skills.

The present double-blind sham-controlled study is aimed at evaluating the effectiveness and long-lasting effect of left anodal/right cathodal tDCS in reading performance of children and adolescent with dyslexia. The concurrent anodal stimulation of the left parieto-temporal region and cathodal stimulation of the right parieto-temporal region was designed to increase left parieto-temporal cortex activation and to reduce right parieto-temporal cortex activation, based on hypothesis that tDCS could induce a normalization of abnormal brain activity observed in children with dyslexia during reading tasks.

Specifically, in individuals with dyslexia a reduced left temporo-parietal cortex activation and an increased right hemisphere activation has been found during phonological processing (Hoeft et al., 2007) and non-word and real word reading (Shaywitz et al., 2002). It has also been documented that successful remedial treatment improves not only reading ability in dyslexics but modifies the activation in these critical brain areas, increasing the left parieto-temporal activity and decreasing the right parieto-temporal activity (Temple et al., 2003, Simos et al., 2002). Similarly, in normal readers data showed that the increase in the left parieto-temporal activity and the decrease in the right parieto-temporal activity is associated with higher reading performance (Yeatman et al., 2011; Turkeltaub et al., 2003) and that the bilateral tDCS on parietal regions positively affect reading (Turkeltaub et al., 2012). Therefore, we hypothesized that the dual action of left anodal and right cathodal tDCS would improve reading efficiency in our participants with dyslexia.

Given the positive effect of coupling neuromodulation techniques with cognitive training (Floel et al., 2008; Bolognini et al., 2009; McArthur et al., 2012), in the present study tDCS was combined with a cognitive training to improve reading speed and accuracy. The tolerability of tDCS was also examined by assessing the short-term adverse effects, during treatment, and the long-term adverse effects.

It was expected that multiple sessions of active tDCS would enhance reading abilities of children and adolescents with dyslexia and that the benefit would be maintained one month after the end of treatment. A specific ameliorative effect may be predicted on tasks primarily requiring phonological processing as non-words and low frequency words reading, rather than high frequency words, since left parieto-temporal cortex has been found to be involved in phonological processing and grapheme-to-phoneme mapping both in patients with brain lesions (Friedmann et al., 1993; Greenwald, 2001) and in typically readers (Valdois et al., 2006; Jobard et al., 2007). Moreover, an improvement in non-word reading and text reading can be also predicted based on our previous studies with TMS, showing such ameliorative effect in adults with dyslexia after facilitation of left parietal and left temporal regions, respectively.

2. Methods

2.1. Participants

The study included eighteen children and adolescents with dyslexia. The diagnosis of dyslexia was based on the DSM-5 criteria (American Psychiatric Association, 2013) and was made with a comprehensive diagnostic battery, including word and non-word lists (Sartori et al., 2007; Stella & Tintoni, 2007) and text reading tests (Cornoldi et al., 2010; Cornoldi & Colpo, 2012). Each participant was evaluated at the Child Neuropsychiatric Unit of the Bambino Gesú Children Hospital by a team of expert clinicians, including a Psychologist, a Neurologist and a Speech Therapist. He/she was included in the study when the speed or accuracy in text and/or word and/or non-word reading task was at least 1.5 standard deviations below the population mean for age. None of the participants had a personal history of neurological disease or a family history of epilepsy, and none had comorbidity with attention deficit or hyperactivity disorder as assessed by clinical examination and by the Conners' Rating Scales – Revised (Conners, 2007). All participants were native Italian speakers, had normal or corrected-to-normal vision, and were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971).

Written informed consent was obtained from all participants and their parents after the procedures had been fully explained. This study was performed in accordance with the World Medical Association's Declaration of Helsinki and The Research Ethical Committee of the Bambino Gesú Children Hospital approved this study under process number 201201X002931.

2.2. Study design

In the present double-blind sham-controlled study, all participants were randomly assigned to one of two different experimental conditions: left anodal/right cathodal tDCS (active group) and sham tDCS (sham group) combined with a cognitive reading training. The active group included 9 participants (5 females) with age range 10.9–17.1 years (mean age 13.2, $SD = 2.6$ years). The sham group included 9 participants (7 females) with age range 10.1–16 years (mean age 13.6, $SD = 2.1$ years).

Each participant was exposed to eighteen 20 minute-sessions of treatment and, independently whether he/she belonged to the active group or to the sham group, received 3 sessions per week for 6 weeks with a minimum inter-session interval of 48 hours. Outcome reading measures were assessed before (T0), immediately after the treatment (T1), and one month after the end of the treatment (T2), by an investigator who was blind to the treatment condition. Both the participants and the trainer, who conducted the cognitive training during both active tDCS and sham tDCS, were blind to the tDCS treatment condition. Only the experimenter, who applied tDCS, was aware of the treatment condition (active or sham). The treatment sessions were conducted at the Bambino Gesú Children Hospital. See Fig. 1 for a schematic representation of the study design.

2.3. Materials

2.3.1. Outcome reading measures

Participants were submitted to reading aloud tasks at T0, T1, and T2, including a text over 400 syllables long (TEXT), a list of 20 high frequency words (HF - 10 trisyllabic and 10 bisyllabic), 20 low frequency words (LF - 10 trisyllabic and 10 bisyllabic), and 20 non-words, created by rearranging the character string of real word items (NW - 10 trisyllabic and 10 bisyllabic). TEXT was written with Times New Roman font, size 13, single-spaced, justified, on a white sheet of A4 paper. HF, LF, NW were arranged in 20-item columns, written with Times New Roman, size 13, single-spaced, on a white sheet of A4 paper. TEXT derived from an Italian novel (Calvino, 1963). A behavioral pre-test has been conducted with 14 children and adolescents, typically readers, (seven females) to select the four equivalent sets of stimuli (from a pool of nine sets of texts, words, and non-words), so that they were comparable in reading speed (total time in seconds) and in number

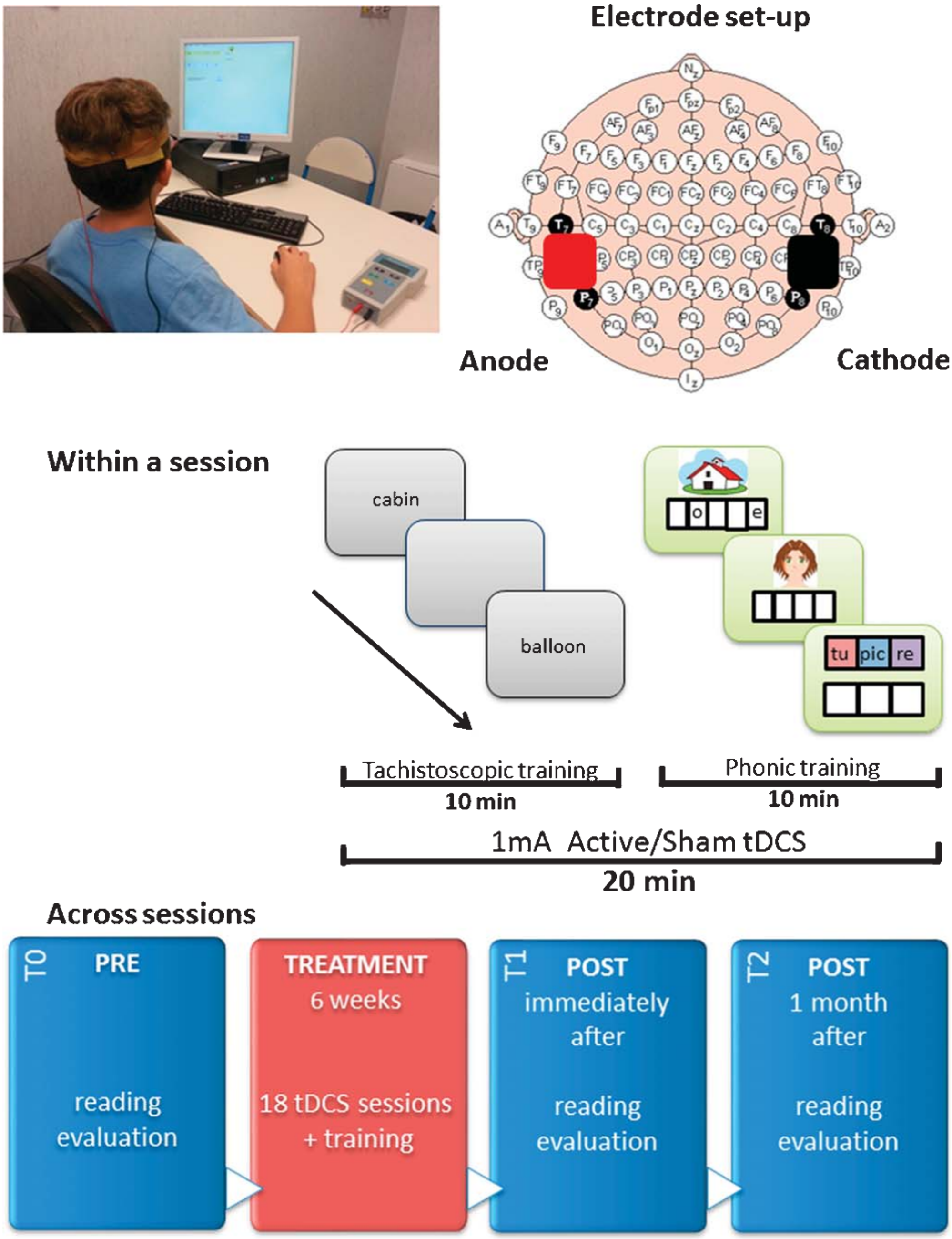

Fig. 1. Schematic representation of the study design and the methods. Experimental design (Top). Participants were exposed to 20 minute-sessions of treatment, 3 times per week, for 6 weeks. Outcome measures were assessed before (T0), immediately after the treatment (T1) and one month after the end of the treatment (T2). Set-up (Middle). Direct current was delivered via a pair of identical, square, scalp electrodes (5 × 5 cm) made of conductive rubber and covered with saline soaked synthetic sponges. In both active and sham conditions the anodal electrode were positioned over the left parieto-temporal region according to the 10–20 EEG on the sites corresponding midway between P7 and TP7. The cathodal electrode was placed on the right side of the parieto-temporal region corresponding midway between P8 and TP8. During the stimulation session participants sat about 40 cm away from the screen and performed the reading training. Cognitive training session (Bottom). Each session included 20 minutes of 1 mA tDCS (Active or Sham) combined with a cognitive training, based on 10 minutes of tachistoscopic presentation of verbal stimuli (tachistoscopic training) to improve reading speed, and on 10 minutes of a phonic training, focused on letter-sound rules (phonic training), to improve reading accuracy.

of errors. Items in HF list and LF list were matched for Italian written word frequency, number of letters and syllables, bigram frequency (according to CoLFIS, http://www.istc.cnr.it/material/database/colfis/) and mean onset reaction times (Barca et al., 2002). Different sets of reading tasks were employed at T0, T1, and T2. The tasks assignment were randomly determined.

Reading errors of each task (TEXT, HF, LF, and NW) were scored as follows: one point was given for each letter substitution (i.e. errors that involved consonant or vowel sound changes, omissions, position changes or additions) and half a point for every self-correction and hesitation, as a measure of reading accuracy. No more than one error point was given for the same item. TEXT reading speed was calculated, by dividing the total time for completion of the reading by the total number of syllables spoken and multiplied per 100. HF, LF and NW reading speed was calculated as the total time (in seconds) spent to read the list. Responses were recorded using a portable recorder to allow the investigator to re-check the score.

2.3.2. Safety and tolerability

Symptoms or side-effects were assessed by a standard questionnaire (Brunoni et al., 2011) which was completed by the participants after each stimulation session (total sessions 324). The questionnaire lists the adverse effects such as: headache, neck pain, scalp pain, tingling, itching, burning sensation, skin redness, sleepiness, trouble concentrating and acute mood change. Participants quantify the intensity of the symptoms or side effects related to tDCS (1, absent; 2, mild; 3, moderate; 4, severe).

2.4. Procedures

2.4.1. Stimulation

2.4.1.1. Active tDCS. Direct current was generated by a BrainStim stimulator by E.M.S. s.r.l. (Bologna, Italy) and delivered via a pair of identical, square, scalp electrodes (5 × 5 cm) made of conductive rubber and covered with saline soaked synthetic sponges. In the active condition, anodal electrode was positioned over the left parieto-temporal regions according to the 10–20 EEG on the sites corresponding midway between P7 and TP7. The cathodal electrode was placed on the right side of the parieto-temporal regions, corresponding midway between P8 and TP8, which was chosen to exclude brain regions typically engaged in reading processes as the frontal and the occipital cortices (Eckert, 2004; Richlan, 2014). At the beginning of the active tDCS, the current was increased slowly during the first 30 seconds to 1 mA the stimulation threshold (ramp-up) and, at the end of the stimulation, the current was decreased slowly to 0 mA during the last 30 seconds (ramp-down). Between the ramp-up and ramp-down constant direct current (1 mA) has been delivered, for 20 minutes. The current density was 0.04 mA/cm^2.

2.4.1.2. Sham tDCS. In the sham condition, stimulation was applied using the same active tDCS setup (left anodal and right cathodal) on the sites corresponding midway between P7 and TP7 and the sites corresponding midway between P8 and TP8, but the current was applied for only 30 seconds. The current was ramped-up from 0 mA to 1 mA to match the ramp-up of the active condition. This placebo-condition provides sensations (e.g., tingling) associated with tDCS to be indistinguishable by the participants from active condition (Gandiga et al., 2006).

2.4.2. Cognitive training

During both active tDCS and sham tDCS the participants, who were blind to the treatment condition (active or sham), underwent to a cognitive training (20 minutes) based on tachistoscopic presentation of verbal stimuli (10 minutes) to improve reading speed, and on a phonic training (10 minutes) focused on letter-sound rules to improve reading accuracy.

Reading speed was trained by a tachistoscopic presentation of words on the PC screen (Schneider & Shiffrin, 1977; Logan, 1978). Participants sat about 40 cm away from the screen (no head restraints) and a word (four- to seven letters length), flashed at the center of the visual field (lower case letters) at a specific reading speed (ranging from 100 to 500 milliseconds). Stimulus materials comprised a total of 30 lists made of 20 high frequency words according to the Italian written word frequency based on CoLFIS, http://www.istc.cnr.it/material/database/colfis/), that differed from reading measures used for outcome assessment. The accuracy has been computed, and one point error was assigned when the participants did not correctly read the word. When reading accuracy reached 80% (within or between sessions), higher complexity level of stimuli were presented (a list of longer words or with reduced presentation times). The same list of words could have been re-presented after 4 sessions, or more, with reduced presentation times. Participants were instructed to read aloud as rapidly as possible the word presented on the screen and were always encouraged to give a response (always try to say a word). The responses given by the participants were recorded, using a portable recorder, to allow the trainer to re-check the score.

The phonic training was focused on letter-sound rules, and analysis of reading and writing at the subword level to improve reading accuracy. The phonic training session included three tasks randomly presented on a computer screen. Participant had to look at the picture of a word and, in the first task, they had to find the missing letters of the word or, in the second task, they had to find the word fitted all blank space. Each of the two tasks lasted three minutes. The third task lasted 4 minutes and consisted of syllables presented on a computer screen that had to be rearranged, to find a real word. Stimulus materials comprised four 150-word lists and 300 colored pictures. Each list comprised words with the same length, in terms of number of letters (four- to seven letters length words). One-point errors were assigned when the participants did not correctly identify the word. When the participants reached 80% of accuracy (within or between sessions), words which were one letter longer were presented.

2.5. Data analysis

Difference between the two groups with dyslexia at baseline (active vs sham) was tested by one-way ANOVAs. To evaluate the effect of treatment, repeated measure ANCOVAs were performed on each reading measure (TEXT, HF, LF, and NW reading errors and speed) with Group (active vs sham) and Time (T0, T1, T2) as the independent factors. Even if groups did not differ for age, potential effects of age have been taken in consideration, by including participants' age at the baseline, as a covariate. To further test the effect of active condition, changes in reading performance, calculated by subtracting the baseline of each reading measure (T0) from the post-treatment reading measure (T1 and T2), were also compared between groups. Repeated measure ANCOVAs, with Group (active vs sham) and Time (T1-T0 and T2-T0) as the independent factors and chronological age at the baseline as covariate were run per each reading change measure.

Post-hoc analyses were performed using Fisher's LSD test. Partial eta squares (ηp^2) have been reported as effect size measures. A p value less than 0.05 was considered as statistically significant. Sphericity was verified by Mauchly's sphericity test.

3. Results

3.1. Demographic measures

Active and sham group did not differ for chronological age [F (1, 16) = 0.16, $p = 0.70$] and for non-verbal IQ, as assessed by Coloured Progressive Matrices (Raven, 2008a, 2008b) [F (1, 16) = 1.81, $p = 0.20$; active group IQ: mean 111.8, $SD = 12.2$; sham group IQ: mean 104.8, $SD = 10.1$].

3.2. Outcome measures

3.2.1. Reading measures at baseline

The active and sham groups did not differ in reading measures at the baseline (see Table 1 for details): T0 errors [$F(1, 16) = 0.10$, $p = 0.75$; HF, $F(1, 16) = 0.36$, $p = 0.85$; LF, $F(1, 16) = 0.55$, $p = 0.47$; NW, $F(1, 16) = 0.01$, $p = 0.93$] and T0 speed [TEXT, $F(1, 16) = 0.07$, $p = 0.80$; HF, $F(1, 16) = 0.25$, $p = 0.62$; LF, $F(1, 16) = 0.23$, $p = 0.64$; NW, $F(1, 16) = 1.68$, $p = 0.21$].

3.2.2. Reading measures after treatment

3.2.2.1. Reading errors. Table 2 showed mean reading errors and speed per each measure in the active and sham group before treatment (T0), after treatment (T1) and one month later (T2). Results showed only a significant Group X Time effect in LF task [$F(2, 30) = 3.59$; $p = 0.04$, $\eta p^2 = 0.19$] due to the reduction of errors after treatment in the active group.

While the active group reduced the errors immediately after treatment (T1 vs T0: $p = 0.03$) and one month later (T2 vs T0: $p = 0.007$), no significant difference emerged in the sham group after the treatment compared to baseline (T1 vs T0: $p = 0.18$; T2 vs T0: $p = 0.34$).

Analysis on errors changes (see Fig. 2) confirmed a Group effect in LF task [$F(1, 15) = 6.29$; $p = 0.02$, $\eta p^2 = 0.30$], showing that the active group had a greater error reduction than the sham group (less errors compared to baseline).

3.2.2.2. Reading speed. Results on reading speed (see Table 2 for details) showed a significant Group X Time effect in NW task [$F(2, 30) = 3.52$; $p = 0.04$, $\eta p^2 = 0.19$], since reading speed in NW task significantly improved in the active group immediately after treatment (T1 vs T0: $p < 0.001$) and the effect persisted also one month after (T2 vs T0: $p < 0.001$). In the sham group, no difference emerged in the

Table 1

Demographic data, IQ and Reading Measures at T0 of Active and Sham group

Group	Subject	Sex	Age	IQ^a	TEXT		HF		LF		NW	
					Err	Spe^a	Err	Spe^b	Err	Spe^b	Err	Spe^b
Active	1	M	11y9m	102	6	41.4	0.5	23	1.5	26	2	30
Active	2	F	16y8m	136	1	18.2	0	9	2	13	0	18
Active	3	M	10y9m	98	15.5	62.7	2	28	4	48	4	68
Active	4	F	11y11m	110	23.5	43.4	4.5	26	5.5	53	13	89
Active	5	M	11y6m	100	12.5	28	0	11	2.5	20	4	30
Active	6	M	12y6m	110	5.5	48.5	0	20	2	28	0	33
Active	7	F	11y3m	110	16.5	47.3	2	21	2.5	25	6.5	35
Active	8	F	17y1m	118	3	31.2	1	15	1	20	0.5	33
Active	9	F	14y8m	123	5.5	38	0	13.5	0.5	17.2	2.5	29
Sham	10	F	11y1m	120	18.5	32	2	12	2	19	7	27
Sham	11	M	11y1m	110	23.5	76	1.5	30	4	58	9	41
Sham	12	F	12y4m	112	6	26.3	1	11	1.5	1.5	2	18
Sham	13	F	15y6m	94	8	24	0.5	16	0.5	23	0	26
Sham	14	M	12y6m	117	3.5	46	1	15	1	21	2	41
Sham	15	F	16y	100	5	24	1	12	0	10	4	23
Sham	16	F	16y	97	13	34.6	1	18	4	23	2	31
Sham	17	F	15y6m	93	2.5	29.3	0	22	0	23	0	31
Sham	18	F	12y2m	100	19.5	50	3	17	3.5	41	8	34

Note: *y* = years; *m* = months; Err = errors; Spe = speed; ^{a}seconds/sillables × 100; ^{b}seconds. TEXT: text; HF: high frequency words; LF: low frequency words; NW: non-words.

Table 2

Mean reading errors and speed (standard deviation) in the outcome reading measures of the active and sham group, before treatment (T0), after treatment (T1) and one month after the end of the treatment (T2)

	ACTIVE			SHAM		
	T0	T1	T2	T0	T1	T2
TEXT						
Errors	9.9 (7.5)	7.5 (5.5)	6.1 (4.4)	11.1 (7.8)	13.2 (13.9)	9.8 (11.1)
Speed^a	39.9 (13.0)	36.8 (14.9)	34.5 (11.9)	38.0 (17.0)	37.7 (18.8)	34.9 (15.9)
HF						
Errors	1.1 (1.5)	0.4 (0.6)	0.4 (0.6)	1.2 (0.9)	1.1 (1.8)	0.7 (0.8)
Speed^b	18.5 (6.7)	15.4 (5.8)	16.0 (8.8)	17.0 (6.0)	15.2 (4.8)	15.7 (7.3)
LF						
Errors	2.4 (1.5)	1.4 (1.8)*	1.2 (1.2)*	1.8 (1.6)	2.4 (1.7)	1.4 (1.8)
Speed^b	27.8 (13.7)	23.1 (9.9)	20.5 (8.6)	24.4 (16.5)	26.0 (13.6)	22.8 (12.0)
NW^b						
Errors	3.6 (4.1)	2.1 (2.3)	2.3 (2.3)	3.8 (3.4)	2.6 (3.0)	2.6 (2.5)
Speed^b	40.6 (22.7)	25.6 (10.5)**	24.9 (11.9)**	30.2 (7.7)	28.1 (12.2)	26.4 (10.5)

Note: ^{a}seconds/sillables × 100; ^{b}seconds; *significant difference from T0, $p < 0.05$; **significant difference from T0, $p < 0.001$. TEXT: text; HF: high frequency words; LF: low frequency words; NW: non-words.

reading speed after treatment compared to baseline (T1 vs T0: $p = 0.58$; T2 vs T0: $p = 0.32$).

Analysis on speed changes confirmed a Group effect in NW task [$F(1, 15) = 4.63$; $p = 0.048$, $\eta p^2 = 0.24$], showing that the active group had faster reading speed than sham group (see Fig. 2).

3.3. *Safety and tolerability*

No participant asked to stop the study or reported significant discomfort at the electrode sites. The main adverse effects (reported by 2 participants in the active group and 2 participants in the sham group), were a tingling and an itching sensation, which diminished rapidly due to habituation; burning sensation (2 participants in the active group and 1 participant in the sham group); and local redness (2 participants in the active group), mostly in the mild intensity (see Table 3).

Headache, sleepiness and trouble concentrating, have not been reported. No psychological symptoms, such as acute mood changes and irritability, nor other discomforts or adverse effects were reported.

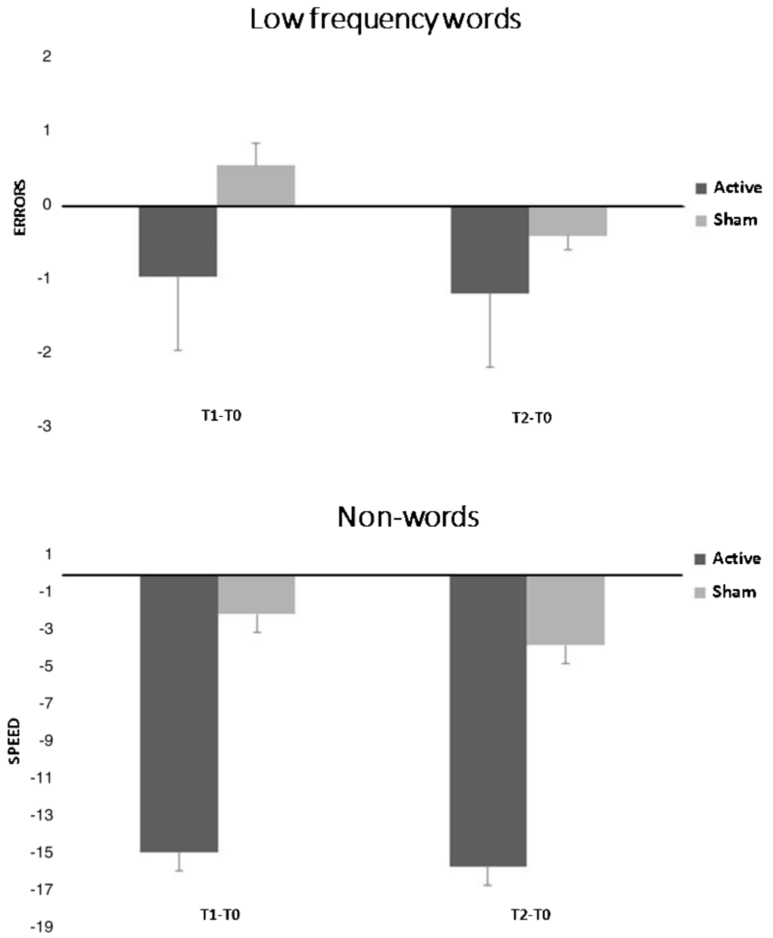

Fig. 2. Reading changes after tDCS treatment in the participants receiving active tDCS (Active) and sham tDCS (Sham) combined with the cognitive training. After tDCS treatment, groups differed in error changes on low frequency word task (Top), since the active group showed overall greater changes (reduction in errors) than the sham group. Difference in reading speed changes (in seconds) was found in non-words task (Bottom), since the active group showed overall greater changes (faster reading speed) than the sham group. *Note:* T1-T0: reading change score calculated by subtracting the baseline measure (T0) from the post-treatment reading measure (T1); T2-T0: reading change score calculated by subtracting the baseline measure (T0) from the one month follow-up measure (T2).

Table 3

Percentage of adverse effects reported by participants

Adverse effect	Mild (%)	Moderate (%)	Severe (%)
Headache	0.0	0.0	0.0
Neck pain	0.0	0.0	0.0
Scalp pain	0.0	0.0	0.0
Tingling	25.0	0.0	0.0
Itching	25.0	0.1	0.0
Burning sensation	12.5	7.7	0.0
Local redness	12.5	0.0	0.0
Sleepiness	0.0	0.0	0.0
Trouble concentrating	0.0	0.0	0.0
Acute mood changes	0.0	0.0	0.0
Irritability	0.0	0.0	0.0

Moreover, none of the participants followed up one month after the end of the treatment reported any discomfort or adverse effect.

4. Discussion

The present double-blind sham-controlled study evaluated the efficacy of tDCS in improving reading abilities in young populations with dyslexia based on hypothesis that tDCS could induce a normalization of their abnormal brain activity during reading tasks.

Our results support the hypothesis that the enhancement of left parieto-temporal cortex lateralization produces reading improvement in children and adolescents with dyslexia who received the active treatment combined with the cognitive training. Specifically, the active treatment, compared to the sham treatment, had a positive effect in ameliorating non-word reading speed and low frequency reading errors and may be interpreted as evidence for a network involved in letter-sound rules affected by tDCS. Our results are in accordance with data reporting evidence of left parieto-temporal cortex involvement in phonological processing and grapheme-to-phoneme mapping in typically readers (Valdois et al., 2006; Jobard et al., 2007). Indeed, the posterior sector of the Visual Word Form Area - a portion of the left fusiform gyrus that is particularly selective for written strings (Dehaene and Cohen, 2011) - projects preferentially to temporal lobe regions and inferior parietal regions, that are thought to encode single letters or graphemes in typically readers (Bouhali et al., 2014). The key role of the left inferior parietal lobule in sequential computations and grapheme transduction has also been underlined in population with dyslexia (Pugh et al., 2000, 2001). The relationship between the left inferior parietal lobule and non-word reading is also supported by neuropsychological data deriving from patients with left angular and supramarginal gyri lesions in which a selective impairment of grapheme-to-phoneme conversion has been found (Friedmann et al., 1993; Greenwald, 2001).

However, the positive effect on high frequency words and text reading was not found in our study. The lack of strong focality of tDCS, using large two electrode montages, should be taken into account as a possible explanation for these missing effects. We can suppose that, with the large two electrode bilateral montages, the current may flow outwards the precise location targeted (Jacobson et al., 2012; Datta et al., 2011; Wagner et al., 2007). Specifically for our study, the current flow may diffuse from the parieto-temporal regions to the bordering parietal regions, which are specially involved in grapheme to phoneme conversion. This possibility might contribute to clarify why in our study active tDCS affected tasks more requiring phonological processing than whole-word or contextual reading processing. With some exceptions (Minhas et al., 2012), computational modeling for a better understanding of individual variation in the current flow pattern is still needed, especially in pediatric populations. As suggested (Turkeltaub et al., 2012), targeting enhancement or inhibition using more focal brain stimulation techniques, as TMS, will help to further delineate the locus of the effect within the parieto-temporal regions and may help to optimize electrode placement for clinical applications of tDCS in dyslexia. Indeed, we have previously observed with TMS (Costanzo et al., 2012, 2013) distinct reading effects between parietal region stimulation (mainly affecting non-word reading) and temporal region stimulation (mainly affecting text reading). Nevertheless, tDCS studies, stimulating the posterior ventral reading system, e.g. the middle and inferior temporal gyrus (Dehaene et al., 2005; Vinckier et al., 2007) could be designed to evaluate the effect on reading due to neural circuits which are more involved in whole-word and text reading (Helenius et al., 1998).

In the present study, we combined tDCS with cognitive training, leaving open the question of whether the active tDCS solely might provide an effect on reading and whether this effect might differ from the combined effect. Currently, nothing is known about the effectiveness of the concurrent application of brain-cognitive rehabilitation approaches in dyslexia, and present study provided preliminary evidence that the combination of active tDCS with cognitive training positively affects some aspects of reading, compared to the cognitive training alone, in our group of children and adolescents with dyslexia. Moreover, the lack of a significant effect in reading in the sham group could be related to the characteristics of the paradigm adopted for the cognitive training. It is possible that the duration and the intensity of the training (eighteen 20 minute-sessions of tachistoscopic and phonic training for six weeks) are not enough to significantly affect reading measures.

However, a recent systematic review on 13 studies documented that tDCS delivered in combination with cognitive training enhances performance on tasks across a range of cognitive functions in healthy and cognitively impaired participants (Elmasry et al., 2015). Previous data showed in healthy adults that single (Floel et al., 2008) or multiple sessions (Meinzer et al., 2014) of anodal tDCS over the posterior languages areas combined with verbal learning enhanced linguistic abilities. Also in clinical populations with focal brain lesions and Alzheimer Disease, anodal tDCS over the left frontal cortex combined with linguistic cognitive training produced positive results on linguistic abilities (Baker et al., 2010; Vines et al., 2011; Cotelli et al., 2014). Further studies are still needed to prove, in the same study, faster and more beneficial therapeutic effect of brain stimulation in conjunction with behavioral therapy (Miniussi & Rossini, 2011) compared to the effect of tDCS solely.

Finally, our results support long-term effects in low frequency-word and in non-word reading even one month after the end of treatment. Long-lasting effects of combined tDCS and cognitive training have been found in literature. When repeated learning sessions of motor learning were combined with active tDCS over the primary motor cortex in healthy adults, positive effects on motor skills were demonstrated three months after the training (Reis et al., 2009). Similarly, repeated sessions of numerical symbols learning combined with tDCS over parietal region improved numerical skills in healthy adults and the effect was still present 6 months after the training (Cohen et al., 2010). The long-lasting modifications have been interpreted as the effect of the modulation of post-synaptic connections similar to long-term potentiation critical for learning and neuroplasticity (Stagg & Nitsche, 2011; Meinzer et al., 2014). As pointed out by others (Iuculano & Cohen Kadosh, 2014), stimulation protocols that induce long-term modifications are of extreme importance to promote tDCS as an effective rehabilitation tool for learning disabilities. Further research and clinical effort are needed to confirm long-term effect in reading in a larger sample.

The present explorative study gives first evidence of enhancement in reading of children and adolescents with dyslexia by non-invasive brain stimulation and serves to strengthen tDCS as a useful and tolerable tool in the pediatric population. Indeed, based on the analysis of 324 tDCS sessions and on one month follow-up evaluations, this study also demonstrates that tDCS is easily tolerated in children and adolescents.

Our results may become a starting point for setting parameters that could be used to devise new rehabilitation strategies in dyslexia for time reduction and cost savings. Due to the reading centrality in aid of other learning, it is critical to remediate reading problems in a timely and effective manner. Present preliminary findings, highlight the pressing need to further explore in clinical trials with large number of participants the extent of potential beneficial of tDCS for the treatment of dyslexia.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

American Psychiatric Association (2013). *Diagnostic and Statistical Manual of Mental Disorders (Fifth ed.).* Arlington, VA: American Psychiatric Publishing.

Aylward, E.H., Richards T.L., Berninger, V.W., Nagy, W.E., Field, K.M., Grimme, A.C., et al. (2003). Instructional treatment associated with changes in brain activation in children with dyslexia. *Neurology*, *61*(2), 212-219.

Baker, J.M., Rorden, C., & Fridriksson, J. (2010). Using transcranial direct current stimulation to treat stroke patients with aphasia. *Stroke*, *41*(6), 1229-1236.

Barca, L., Burani, C., & Arduino, L.S. (2002). Word naming times and psycholinguistic norms for Italian nouns. *Behavior Research Methods, Instruments & Computers*, *34*(3), 424-434.

Bolognini, N., Pascual-Leone, A., & Fregni, F. (2009). Using non-invasive brain stimulation to augment motor training-induced plasticity. *Journal of NeuroEngineering and Rehabilitation*, *6*, 8. doi: 10.1186/1743-0003-6-8

Bolognini, N., Vallar, G., Casati, C., Latif, L.A., El-Nazer, R., Williams, J., & Fregni, F. (2011). Neurophysiological and Behavioral Effects of tDCS Combined With Constraint-Induced Movement Therapy in Poststroke Patients. *Neurorehabilitation & Neural Repair*, *25*(9), 819-829. doi: 10.1177/1545968311411056

Bouhali, F., Thiebaut de Schotten, M., Pinel, P., Poupon, C., Mangin, J.F., Dehaene, S., & Cohen, L. (2014). Anatomical connections of the visual word form area. *The Journal of Neuroscience*, *34*(46), 15402-15414. doi: 10.1523/JNEUROSCI.4918-13.2014

Brunoni, A.R., Amadera, J., Berbel, B., Volz, M.S., Rizzerio, B.G., & Fregni, F. (2011). A systematic review on reporting and assessment of adverse effects associated with transcranial direct current stimulation. *International Journal of Neuropsychopharmacology*, *14*(8), 1133-1145. doi: 10.1017/S1461145710001690

Calvino, I. (1963). *Marcovaldo.* Torino, Italy: Einaudi.

Cohen Kadosh, R., Soskic, S., Iuculano, T., Kanai, R., & Walsh, V. (2010). Modulating neuronal activity produces specific and long-lasting changes in numerical competence. *Current Biology*, *20*(22), 2016-2020. doi: 10.1016/j.cub.2010.10.007

Conners, C.K. (2007). *Conners' Rating Scales-Revised.* Italian adaptation by M. Nobile, B. Alberti, & A. Zuddas. Firenze, Italy: Giunti OS.

Cornoldi, C., & Colpo, G. (2012). *Nuove Prove di lettura MT per la Scuola Secondaria di I Grado.* Firenze, Italy: Giunti OS.

Cornoldi, C., Pra Baldi, A., Friso, G., Giacomin, A., Giofrè, D., & Zaccaria, S. (2010). *Prove MT Avanzate di Lettura e Matematica 2 per il biennio della scuola superiore di II grado.* Firenze, Italy: Giunti OS.

Costanzo, F., Menghini, D., Caltagirone, C., Oliveri M., & Vicari, S. (2013). How to improve reading skills in dyslexics: The effect of high frequency rTMS. *Neuropsychologia*, *51*(14), 2953-2959. doi: 10.1016/j.neuropsychologia.2013.10.018

Costanzo, F., Menghini, D., Caltagirone, C., Oliveri, M., & Vicari, S. (2012). High frequency rTMS over the left parietal lobule increases non-word reading accuracy. *Neuropsychologia*, *50*(11), 2645-2651. doi: 10.1016/j.neuropsychologia.2012.07.017

Cotelli, M., Manenti Brambilla, M., Petesi, M., Rosini, S., Ferrari, C., & Miniussi, C. (2014). Anodal tDCS during face-name associations memory training in Alzheimer's patients. *Frontiers in Aging Neuroscience*, *6*, 38. doi: 10.3389/fnagi.2014.00038

Datta, A., Baker, J.M., Bikson, M., & Fridriksson, J. (2011). Individualized model predicts brain current flow during transcranial direct-current stimulation treatment in responsive stroke patient *Brain Stimuation*, *4*(3), 169-174. doi: 10.1016/j.brs.2010.11.001.

Dehaene S., & Cohen L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences*, *15* (6), 254–262.

Dehaene., S., Cohen, L., Sigman, M., & Vinckier, F. (2005).The neural code for written words: A proposal. *Trends in Cognitive Sciences*, (7), 335-341.

Eckert, M. (2004). Neuroanatomical markers for dyslexia: A review of dyslexia structural imaging studies. *Neuroscientist*, *10*(4), 362-371.

Eden, G.F., Jones, K.M., Cappell, K., Gareau, L., Wood, F.B., Zeffiro, T.A., et al. (2004). Neural changes following remediation in adult developmental dyslexia. *Neuron*, *44*(3), 411-422.

Elmasry, J., Loo, C., & Martin, D. (2015). A systematic review of transcranial electrical stimulation combined with cognitive training. *Restorative Neurology and Neuroscience*, *33*(3), 263-278. doi: 10.3233/RNN-140473

Ferrer, E., Shaywitz, B.A., Holahan, J.M., Marchione, K., & Shaywitz, S.E. (2010). Uncoupling of reading and IQ overtime: Empirical evidence for a definition of dyslexia. *Psychological Science*, *21*(1), 93-101. doi: 10.1177/0956797609354084

Floel, A., Rosser, N., Michka, O., Knecht, S., & Breitenstein, C. (2008). Noninvasive brain stimulation improves language learning. *Journal of Cognitive Neuroscience*, *20*(8), 1415-1422. doi: 10.1162/jocn.2008.20098

Friedman, R.F., Ween, J.E., & Albert, M.L. (1993). Alexia. In K.M. Heilman, E. & Valenstein, E (eds), *Clinical neuropsychology* (pp. 37-62). New York, US: Oxford University Press.

Frye, R.E., Rotenberg, A., Ousley, M., & Pascual-Leone, A. (2008). Transcranial magnetic stimulation in child neurology: Current and future directions. *Journal of Child Neurology*, *23*(1), 79-96.

Gandiga, P.C., Hummel, F.C., & Cohen, L.G. (2006). Transcranial DC stimulation (tDCS): A tool for doubleblind sham-controlled clinical studies in brain stimulation. *Clinical Neuropsychology*, *117*(4), 845-850.

Graves, W., Desai, R., Humpries, C., Seidenberg, M.S., & Binder, J.R. (2010). Neural systems for reading aloud: A multiparametric approach. *Cerebral Cortex*, *20*(8), 1799-1815. doi: 10.1093/cercor/bhp245

Greenwald, M. (2001). Acquired reading disorders. In R. S Berndt, J. Grafman, & F. Boller (eds.), *Handbook of Neuropsychology: Language and Aphasia* (pp. 205-220). Amsterdam, Netherlands: Elsevier.

Helenius, P., Salmelin, R., Service E., & Connolly, J.F. (1998). Distinct time courses of word and context comprehension in the left temporal cortex. *Brain*, *121*(Pt 6), 1133-1142.

Heth, I., & Lavidor, M. (2015). Improved reading measures in adults with dyslexia following transcranial direct current stimulation treatment. *Neuropsychologia*, *70*, 107-113. doi: 10.1016/j.neuropsychologia.2015.02.022

Hoeft, F., McCandliss, B.D., Black, J.M., Gantman, A., Zakerani, N., Hulme, C., et al. (2011). Neural systems predicting long-term outcome in dyslexia. *PNAS, Proceedings of the National Academy of Sciences U S A*, *108*(1), 361-366. doi: 10.1073/pnas.1008950108

Hoeft, F., Meyler, A., Hernandez, A., Juel, C., Taylor-Hill, H., Martindale, J.L., & Gabrieli, D.E. (2007). Functional and morphometric brain dissociation between dyslexia and reading ability. *PNAS, Proceedings of the National Academy of Sciences*, *104*(10), 4234-4239.

Iuculano, T., & Cohen Kadosh, R. (2014). Preliminary evidence for performance enhancement following parietal lobe stimulation in Developmental Dyscalculia. *Frontiers in Human Neuroscience*, *8*, 38. doi: 10.3389/fnhum.2014.00038

Jacobson, L., Goren, N., Lavidor, M., & Levy, D.A. (2012). Oppositional transcranial direct current stimulation (tDCS) of parietal substrates of attention during encoding modulates episodic memory. *Brain Research*, *23*, 1439:66-72. doi: 10.1016/j.brainres.2011.12.036

Jobard, G., Vigneau, M., Mazoyer, B., & Tzourio-Mazoyer, N. (2007). Impact of modality and linguistic complexity during reading and listening tasks. *Neuroimage*, *34*(2), 784-800.

Krause, B., & Cohen Kadosh, R. (2013). Can transcranial electrical stimulation improve learning difficulties in atypical brain development? A future possibility for cognitive training. *Developmental Cognitive Neuroscience*, *6*, 176-194. doi: 10.1016/j.dcn.2013.04.001

Logan, G.D. (1978). Attention in character classification: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General*, *107*, 32-63.

McArthur, G., Eve, P.M., Jones, K., Banales, E., Kohnen, S., Anandakumar, T., & Castles, A. (2012). Phonics training for English-speaking poor readers. *Cochrane Database of Systematic Reviews*, *12*, *CD009115*. doi: 10.1002/14651858.CD009115.pub2

Meinzer, M., Jähnigen, S., Copland, D.A., Darkow, R., Grittner, U., Avirame, K., & Flöel, A. (2014). Transcranial direct current stimulation over multiple days improves learning and maintenance of a novel vocabulary. *Cortex*, *50*, 137-147. doi: 10.1016/j.cortex.2013.07.013

Minhas, P., Bikson, M., Woods, A.J., Rosen, A.R., & Kessler, S.K. (2012). Transcranial direct current stimulation in pediatric brain: A computational modeling study. *IEEE Engineering in Medicine and Biology Society Annual Conference*, *2012*, 859-862. doi: 10.1109/EMBC.2012.6346067

Miniussi, C., & Rossini, P.M. (2011). Transcranial magnetic stimulation in cognitive rehabilitation. *Neuropsychological Rehabilitation*, *21*(5), 579-601. doi: 10.1080/09602011.2011.562689

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113.

Philipose, L.E., Gottesman, R.F., Newhart, M., Kleinman, J.T., Herskovits, E.H., Pawlak, M.A., et al. (2007). Neural regions essential for reading and spelling of words and pseudowords. *Annals of Neurology*, *62*(5), 481-492.

Price, C.J. (2000). The anatomy of language: Contributions from functional neuroimaging. *Journal of Anatomy*, *197*(3), 335-359.

Price, C.J., & Mechelli, A. (2005). Reading and reading disturbance. *Current Opinion in Neurobiology*, *15*(2), 231-238.

Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., et al. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews*, *6*(3), 207-213.

Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., et al. (2001). Neurobiological studies of reading and reading disability. *Journal of Communication Disorders*, *34*(6), 479-492.

Raven, J.C. (2008a). *Coloured progressive matrices*. Italian standardization by C. Belacchi, T. C. Scalisi, E. Cannoni, & C. Cornoldi. Firenze, Italy: Giunti OS.

Raven, J.C. (2008b). *Standard Progressive Matrices*. Firenze, Italy: Giunti OS.

Reis, J., Schambra, H.M., Cohen, L.G., Buch, E.R., Fritsch, B., Zarahn, E., & Krakauerc, J.W (2009). Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *PNAS, Proceedings of the National Academy of Sciences U S A*, *106*(5), 1590-1595. doi: 10.1073/pnas.0805413106

Richlan, F. (2012) Developmental dyslexia: Dysfunction of a left hemisphere reading network. *Frontiers in Human Neuroscience*, *6*, 120. doi: 10.3389/fnhum.2012.00120

Richlan, F. (2014). Functional neuroanatomy of developmental dyslexia: The role of orthographic depth. *Frontiers in Human Neuroscience*, *8*, 347. doi: 10.3389/fnhum.2014.00347

Sartori, G., Job, R., & Tressoldi, P.E. (2007). *DDE-2 Batteria per la Valutazione della Dislessia e della Disortografia Evolutiva-2*. Firenze, Italy: Giunti OS.

Schneider, W., & Shiffrin, R.M. (1977). Controlled and automatic human information processing: Detection, search, and attention. *Psychol Rev*, *84*, 1-66.

Shaywitz, B.A., Shaywitz, S.E., Blachman, B.A., Pugh, K.R., Fulbright, R.K., Skudlarski, P., et al. (2004). Development of left occipitotemporal systems for skilled reading in children after a phonologically- based intervention. *Biological Psychiatry*, *55*(9), 926-933.

Shaywitz, B.A., Shaywitz, S.E., Pugh, K.R., Mencl, W.E., Fulbright, R.K., Skudlarski, P., et al. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry*, *52*(2), 101-110.

Shaywitz, S.E. (1998) Functional disruption in the organization of the brain for reading in dyslexia. *PNAS, Proceedings of the National Academy of Sciences U S A*, *95*(5), 2636-2641.

Shaywitz, S.E., & Shaywitz, B.A. (2008). Paying attention to reading: The neurobiology of reading and dyslexia. *Development and Psychopathology*, *20*(4), 1329-1349. doi: 10.1017/S0954579408000631

Simos, P.G., Breier, J.I., Fletcher, J.M., Foorman, B.R., Castillo, E.M., & Papanicolaou, A.C. (2002). Brain mechanisms for reading words and pseudowords: An integrated approach. *Cerebral Cortex*, *12*(3), 297-305.

Stagg, C.J., & Nitsche, M.A. (2011). Physiological basis of transcranial direct current stimulation. *Neuroscientist*, *17*(1), 37-53. doi: 10.1177/1073858410386614

Stella, G., & Tintoni, C. (2007). Indagine e rilevazione sulle abilità di lettura nelle scuole secondarie di secondo grado. *Dislessia*, *4*(3), 271-285.

Stuss, D.T. (2011). The future of cognitive neurorehabilitation. *Neuropsychological Rehabilitation*, *21*(5), 755-768. doi: 10.1080/09602011.2011.605590

Temple, E., Deutsch, G.K., Poldrack, R.A., Milleri, S.L., Tallali, P., Merzenichi, M.M., et al. (2003). Neural deficits in children with dyslexia ameliorated by behavioural remediation: Evidence from functional MRI. *PNAS, Proceedings of the National Academy of Sciences U S A*, *100*(5), 2860-2865.

Turkeltaub, P.E., Benson, J., Hamilton, R.H., Datta, A., Bikson, M., & Coslett, H.B. (2012). Left lateralizing transcranial direct current stimulation improves reading efficiency. *Brain Stimulation*, *5*(3), 201-207. doi: 10.1016/j.brs.2011.04.002

Turkeltaub, P.E., Eden, G.F., Jones, K.M., & Zeffiro, T.A. (2002). Meta-analysis of the functional neuroanatomy of single-word reading: Method and validation. *Neuroimage*, *16*(3), 765-780.

Turkeltaub, P.E., Gareau, L., Flowers, D.L., Zeffiro, T.A., & Eden, G.F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience*, *6*(7), 767-773.

Valdois, S., Carbonnela, S., Jupharda, A., Baciua, M., Ansa, B., Peyrina, C., et al. (2006). Polysyllabic pseudo-word processing in reading and lexical decision: Converging evidence from behavioral data, connectionist simulations and functional MRI. *Brain Research*, *1085*(1), 149-162.

Vicario, C.M., & Nitsche, M.A. (2013). Non-invasive brain stimulation for the treatment of brain diseases in childhood and adolescence: State of the art, current limits and future challenges. *Frontiers in Systems Neuroscience*, *7*, 94. doi: 10.3389/fnsys.2013.00094

Vinckier, F., Dehaene, S., Jobert, A., Dubus, J.P., Sigman, M., & Cohen, L. (2007). Hierarchical coding of letter strings in the ventral stream: Dissecting the inner organization of the visual word-form system. *Neuron*, *55* (1), 143-156.

Vines, B.W., Norton, A.C., & Schlaug, G. (2011). Non-invasive brain stimulation enhances the effects of melodic intonation therapy. *Frontiers in Psychology*, *2*, 230. doi: 10.3389/fpsyg.2011.00230

Wagner, T., Fregni, F., Fecteau, S., Grodzinsky, A., Zahn, M., & Pascual-Leone, A. (2007). Transcranial direct current stimulation: A computer-based human model study. *Neuroimage*, *35*(3), 1113-1124.

Yeatman, J.D., Dougherty, R.F., Rykhlevskaia, E., Sherbondy, A.J., Deutsch, G.K., Wandell, B.A., & Ben-Shachar, M. (2011). Anatomical properties of the arcuate fasciculus predict phonological and reading skills in children. *Journal of Cognitive Neuroscience*, *23*(11), 3304-3317. doi: 10.1162/jocn_a_00061