



## Review article

# Are transcranial brain stimulation effects long-lasting in post-stroke aphasia? A comparative systematic review and meta-analysis on naming performance

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## ABSTRACT

In the last decade, the effects of NIBS on language recovery in post-stroke aphasia have been evaluated, but little is known about the long-term effectiveness.

To this aim, we conducted a systematic review and meta-analysis to determine whether positive effects, mainly on naming performance, are maintained in time, and rTMS and/or tDCS (either as an add-on therapy to SLT or as monotherapy) can be considered effective and reliable interventions for naming rehabilitation.

Sixteen studies met our inclusion criteria and the pooled SMDs showed a medium to large rTMS effect and a small to medium tDCS effect. Critically, the treatment effects were maintained in time. Sub-analyses indicated that while rTMS can be considered effective for both subacute and chronic patients, tDCS seems adequate only for chronic aphasia. Importantly, the level of evidence as qualified with GRADE was moderate to high for rTMS and low for tDCS studies.

## 1. Introduction

Stroke is the most disabling health condition worldwide in adulthood and a substantial proportion of stroke survivors live with aphasia (Berthier, 2005). Post-stroke aphasia is an acquired language disorder and one of the worst outcomes of stroke, altering some or all modalities of language processing: speech, reading, and writing. The most common causes are left middle cerebral artery infarcts with damage to the cortical and subcortical regions in the left hemisphere; rarely aphasia is due to a right hemisphere lesion. Linguistic impairment can vary, differing in production fluency and level of comprehension, repetition, and word retrieval ability. Symptoms are heterogeneous and can change over time; for instance, patients having one type of aphasia in the acute phase may present a different clinical profile in the chronic phase (Raymer and Gonzalez Rothi, 2017a).

It is estimated that more than 15 million people worldwide suffer from stroke each year (Feigin et al., 2014), aphasia being present in approximately 38% of stroke survivors (Berthier, 2005; Pedersen et al., 2004). Due to early physiological repair mechanisms involving cell genesis, axon growth, and synaptic modulation, the majority of stroke patients achieve some spontaneous recovery, even in the absence of a rehabilitation treatment. Nevertheless, around 40% of these patients

still have significant aphasia one year after stroke and residual symptoms may persist for many years (Lazar et al., 2008; Pedersen et al., 1995).

The economic and social consequences are highly relevant since aphasia has a negative impact on activities of daily living and on people's quality of life (Hilari et al., 2015). Patients with reduced speech and comprehension abilities are more likely to suffer from mood disorders such as depression, social isolation, unemployment, which compromise their psychological wellbeing and put major burdens on their caregivers and on the health-care system (Flowers et al., 2016; Jacquet-Andrieu, 2014). These patients experience longer hospitalization periods, need more intensive health service support, participate in fewer activities and report high distress (Raymer and Gonzalez Rothi, 2015).

Current research demonstrates that aphasia recovery is modulated by many variables including lesion size and site, aphasia type and severity and, to some extent, by the nature of early hemodynamic response, type of treatment, interval between onset and beginning of speech therapy, environmental support etc. (Watila and Balarabe, 2015). After the initial spontaneous recovery following stroke (e.g., blood flow stabilization, resolution of brain swelling), recovery relies on the reorganization of brain networks, which occurs both

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spontaneously and in response to behavioral training (e.g., speech-language therapy) (Fama and Turkeltaub, 2014).

The most widespread current rehabilitation approach for aphasia is speech and language therapy (SLT) (Raymer and Gonzalez Rothi, 2017b). SLT has been proved to reduce language impairment, but treatment is quite expensive, progress is often slow, and effect sizes are sometimes modest (Brady et al., 2016). Even though the degree of spontaneous recovery gradually declines during the first 6–12 months, it is well established that at least partial recovery of language can be reached at any point after stroke, but requires a large amount of time and therapy sessions (“more is better”). A recent study (Stahl et al., 2017) found no added value from more than two hours of daily SLT therapy but instead showed that an increase in treatment duration (even only 2 weeks) contributes significantly to recovery. Unfortunately, because of the limited clinical resources many patients do not receive the recommended amount of training that was estimated at 98.4 h of therapy (Bhagal et al., 2003; Code and Heron, 2003; Saxena and Hillis, 2017).

In an attempt to manipulate the neurotransmitter systems and subsequently facilitate language recovery, different drugs such as memantine, vasopressin, dextroamphetamine, and piracetam, have been tried (Keser et al., 2017; Wortman-Jutt and Edwards, 2017). To date, the findings supporting pharmacological therapy are questionable (Berthier et al., 2011).

In this context, alternative methods for increasing aphasia treatment effectiveness, by either improving the total amount of learning achieved (better results) or by speeding up the learning process (faster results), have been investigated. There is evidence for structural and functional reorganization of language networks after stroke that mediates recovery, and recent research on brain plasticity (Hoogendam et al., 2010; Stagg and Nitsche, 2011) has led to new approaches in stroke rehabilitation. The improvement of aphasia is associated with the reorganization of the balance between the perilesional ipsilateral and contralateral hemispheric activation (Abel et al., 2015; Turkeltaub et al., 2012). Additional therapies, with or without SLT, like non-invasive brain stimulation (NIBS) interventions, have been tried in order to modify the cortical excitability and therefore promote the post-stroke reorganization of language networks (Turkeltaub, 2015).

The most extensively applied protocols in post-stroke aphasia rehabilitation research are based on repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS). Although both rTMS and tDCS are non-invasive stimulation techniques, their functioning principles, and consequently their effects differ; while rTMS induces action potentials in neuronal axons via electromagnetic current, tDCS modulates neural firing rates due to current-induced changes in resting membrane potentials (Bolognini and Miniussi, 2018; Fertonani and Miniussi, 2017; Giordano et al., 2017; Nevler and Ash, 2015; Woods et al., 2016). For a more general overview and background regarding the rTMS and tDCS mechanisms, see (Stagg and Nitsche, 2011; Giordano et al., 2017; Nitsche and Paulus, 2000; Terao and Ugawa, 2002; Klomjai et al., 2015); for example, Krause et al.'s (2017) data indicate that tDCS may act by altering functional connectivity, both locally and between distant brain areas.

TMS and tDCS can excite or inhibit neuronal populations, depending on the stimulation parameters (e.g., high-frequency vs low-frequency rTMS, cathodal vs anodal tDCS), that can last for many minutes after a short session. Equally important, all these factors interact with several other variables related to individual anatomy (e.g., properties of the brain tissue and its location), and the brain's internal state at the time of stimulation, i.e., the initial neural activation state and synaptic plasticity of the stimulated area. In particular, tDCS will affect the performance (improving or decreasing it) depending on the state of the neural population of the stimulated area; being a neuromodulatory technique, it induces firing of neurons that are near threshold while those neurons not activated by the task are less likely to discharge (for details on state-dependent brain stimulation see

(Miniussi et al., 2013; Bergmann, 2018)).

Research shows that post-stroke neuronal reorganization may be beneficial or maladaptive (Di Pino et al., 2014) and tDCS and rTMS could have a therapeutic role by potentially reversing an eventual maladaptive pattern of activation and by creating long-lasting desirable brain changes.

The possibility to modulate brain plasticity by means of rTMS and tDCS and consequently affect behavior opens up new possibilities in this field, but to date, there is still a great deal of uncertainty about the effects of different stimulation parameters and protocols (e.g., inhibitory - decreasing activation in the intact hemisphere, or excitatory - increasing the output of the perilesional region in the damaged hemisphere).

Reviews of tDCS, rTMS and aphasia literature are disproportionately numerous when compared with the number of original experimental studies (ALHarbi et al., 2017; de Aguiar et al., 2015; Sandars et al., 2016; Sebastianelli et al., 2017; Shah-Basak et al., 2016; Wong and Tsang, 2013; Rosso et al., 2018; Elsner et al., 2015; Galletta et al., 2016; Holland and Crinion, 2012; Kapoor, 2017; Li et al., 2015; Mendoza et al., 2016; Otal et al., 2015; Ren et al., 2014). For example, Wortman-Jutt and Edwards (2017) showed that between 2008 and 2015, 48% of publications regarding tDCS and aphasia rehabilitation were review papers. This indicates the huge interest in this topic but also the difficulty in conducting experimental research (i) on a clinical population characterized by great variability (especially regarding lesion type and clinical picture), (ii) in the absence of solid data regarding the underlying mechanisms of these techniques, i.e., without being able to make predictions on their clinical efficacy and (iii) without recommendations or guidelines regarding the NIBS parameters to use (e.g., stimulation area, frequency, intensity, polarity, duration, as monotherapy or coupled with cognitive training, etc.), (iv) taking into consideration the huge amount of time and energy that researchers, patients and caregivers have to invest in this kind of experimental protocols. Current published reviews and meta-analyses, however, provide conflicting evidence and little information on the real utility of NIBS for aphasia, all concluding that more multicenter RCTs, with larger populations and homogenous intervention protocols are required.

Critically, all previously published meta-analyses evaluated NIBS effects immediately after treatment, but monitoring outcome over time after treatment is crucial in order to evaluate which treatment is really effective and which patients might benefit the most. NIBS longer-term results are very important in order to understand their efficacy and safety. In clinical practice, demonstrating a short-term effect of rehabilitation is an insufficient result; what matters is a long-term preservation of positive achievements. In contrast with previous systematic reviews on this topic, which analyzed stimulation effects immediately after treatment, the purpose of this meta-analysis was to systematically synthesize and compare NIBS long-term efficacy in language recovery, in order to verify whether there are new and valid alternatives to improve aphasia treatment, eventually by coupling SLT with rTMS or tDCS. Secondly, because previous studies (Shah-Basak et al., 2016; Otal et al., 2015) revealed a greater positive outcome of rTMS compared to tDCS, we assessed whether the two NIBS effect sizes significantly differed from each other also at follow-up. Furthermore, immediate post-treatment effects were compared with those reported at follow-up to evaluate changes over time. By grouping and contrasting subsets of studies according to different methodological aspects, further sub-analyses investigated potential influences of the study design (such as analysis including only tDCS RCT studies) and the post-stroke interval: chronic (more than six months after stroke) vs subacute (less than six months after stroke). Finally, the online software GRADE Pro GDT was used to qualify the evidence (<https://grade.pro.org>).

## 2. Methods

This systematic review was conducted in accordance to the

**Table 1**  
Summary of patients' characteristics.

ID	Study	NIBS	Overall sample size			Experimental group characteristics			Stroke Interval	Chronic/ Subacute	Mean Stroke Interval	Handedness	Control group	
			Male	Female	Mean Age (SD)	Sample Size	Male	Female					Sample Size	Dropout
1	(Waldowski et al., 2012)	TMS	13	6	7	62.31 ± 11.03, range 38–77	subacute	28.92 ± 19.39 days	right	13	0			
2	(Medina et al., 2012)	TMS	5	4	1	60.60 ± 7.1, range 51–71	chronic	49.8 ± 29.6, range 6–87 months	right	5	0			
3	(Barwood et al., 2013)	TMS	10	4	2	61 ± 7.5, range 54–66	chronic	44.4 ± 15.08, range 31–69 months	right	6	0			
4	(Semiów et al., 2013)	TMS	38	8	11	61.65 ± 11.7, range 38–73	subacute	33.4 ± 24.18, range 11–106 days	right	19	2			
5	(Khedr et al., 2014)	TMS	29	8	11	61 ± 9.8	subacute	40.6 ± 28.50 days	right	10	1			
6	(Tsai et al., 2014)	TMS	53	31	22	62.3 ± 12.1	chronic	17.8 ± 7.2 months	right	22	3			
7	(Wang et al., 2014)	TMS	29	15	14	61.3 ± 13.2	chronic	16.8 ± 6.4 months	right	14	0			
8	(Hu et al., 2018)	TMS	20	10	6	48.5 ± 11.2	chronic	7.5 ± 3.2 months	right	10	0			
9	(Fiori et al., 2013)	tDCS	7	5	2	58.4 ± 9.5, range 44–71	chronic	33.8 ± 27.9, range 7–84 months	right	7	0			
10	(Marangolo et al., 2013a)	tDCS	7	5	2	62.4 ± 9.5, range 46–77	chronic	40.8 ± 26.7, range 7–84 months	right	7	1			
11	(Marangolo et al., 2013b)	tDCS	12	8	4	59.5 ± 8.14, range 44–71	chronic	37.25 ± 22.15, range 7–84 months	right	12	0			
12	(Polanowska et al., 2013)	tDCS	37	18	11	57.6 ± 9.6, range 34–75	subacute	55.7 ± 44.8, range 10–187 days	right	19	4			
13	(Shah-Basak et al., 2015)	tDCS	5	ns	ns	63.6 ± 8.6, range 53–78	chronic	31 ± 29.7, range 7–101 months	right	3	2			
14	(Meinzer et al., 2016)	tDCS	26	13	7	59.9 ± 11.8, range 38–77	chronic	46 ± 24.5, range 15–108 months	right	13	0			
15	(Spielmann et al., 2018)	tDCS	54	23	18	57.9 ± 9.6	subacute	46.9 ± 16.1 days	right	31	4			
16	(Fridriksson et al., 2018)	tDCS	74	34	24	60 ± 11	chronic	44 ± 45 months	right	40	8			

Abbreviations: NIBSnoninvasive brain stimulation methods; SDstandard deviation; tDCSTranscranial direct current stimulation; TMStranscranial magnetic stimulation.  
\*NOTE: the bolded numbers indicate that the same patients were in the treatment and control group, as part of open crossover designs.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2015).

2.1. Literature search and study selection

Four electronic databases - MEDLINE (accessed by PubMed, <https://www.ncbi.nlm.nih.gov/pubmed>), PsycARTICLES (via EBSCOHost, <https://search.ebscohost.com>), PsycINFO (via EBSCOHost) and Web of Science (<https://webofknowledge.com/>) - were searched for studies investigating post-stroke aphasia treatment using either rTMS or tDCS stimulation, alone or combined with other therapies. The considered papers were published between August 2004 and February 2019.

Keywords were: (1) “tDCS”, “transcranial direct current stimulation”; “transcranial magnetic stimulation”, “TMS “AND (2) “aphasia”, “language disorder”.

Studies were selected according to the following inclusion /exclusion criteria:

• **Inclusion criteria:**

- interventions designed for adults with post-stroke aphasia,
- rTMS or tDCS stimulation studies (alone or combined with other therapies),
- rTMS or tDCS were specified as the main intervention/ treatment,
- cephalic stimulation designs only (at least one electrode was positioned on the scalp, the reference electrode could be extra-cephalic, such as on a shoulder),
- minimum 4 weeks (1 month) of follow-up,
- at least four aphasic participants,
- peer-reviewed publications,
- only RCTs or crossover designs,
- published in English,
- when several articles derived from the same study, either with increased recruitment or extended follow-up evaluations, we chose the one with the higher number of participants and the most complete data reported at follow-up,

• **Exclusion criteria:**

- interventions designed for other types of post-stroke disorders or aphasia not due to stroke,
- other types of brain stimulations such as transcranial random noise stimulation, electroconvulsive therapy, etc.,
- open-label studies, e.g. (Naeser et al., 2005; Hara et al., 2015; Harvey et al., 2017),
- studies involving less than 3 stimulation sessions over the same cortical region per patient,
- extra-cephalic stimulation sites, e.g. (Marangolo et al., 2017),
- a short follow-up period (less than one month), e.g. (Cipollari et al., 2015),
- case reports and research studies with less than four participants,
- articles from the gray literature (i.e., literature that is not formally published in sources such as books or journal articles, e.g. unpublished Ph.D. thesis),
- presentations from international meetings with no specific data provided, perspective and opinion publications, case reports, series of cases, previous reviews or meta-analyses,
- studies not published in, or translated into English,
- studies that did not provide adequate information to analyze treatment effects (i.e., when we could not extract useful quantitative data) and we got no reply from the authors.

The retrieved papers were appraised to exclude those that clearly did not satisfy the inclusion/ exclusion criteria as revealed by the title, keywords, abstract or full-text screening; for example, several studies included patients with primary progressive aphasia, had an open-label design (Naeser et al., 2005; Hara et al., 2015; Harvey et al., 2017; Lifshitz Ben Basat et al., 2016), or had a short follow-up period (1–3 weeks). Duplicates were removed through hand search. Additionally, to

**Table 2**  
Summary of disorders' characteristics.

Study	NIBS	Lesion area	Lesion Type	Aphasia Type	Diagnosis criteria and instruments	Aphasia Severity	Outcome	Outcome Evaluation
1 Waldowski et al., 2012	TMS	anterior and posterior language areas	ischemic stroke	all types	BDAE, ASRS	moderate to severe	Naming	Computerized Picture Naming Test (Accuracy)
2 Medina et al., 2012	TMS	left insula, Heschl's gyrus, and Rolandic operculum	ischemic stroke	non fluent	BDAE, BNT, Snodgrass & Vanderwart picture inventory	mild to moderate	Speech	Cookie Theft description: Correct Information Units (Discourse Productivity)
3 Barwood et al., 2013	TMS	left MCA territory (for details see Table 1 – the Barwood et al., 2013 study)	ischemic stroke	non fluent	BDAE, BNT, Snodgrass & Vanderwart picture inventory	mild to severe	Naming	BNT mean scores
4 Seniów et al., 2013	TMS	left MCA territory (for details see Table 1 – Seniów et al., 2013 study)	ischemic stroke	all types	BDAE, ASRS	moderate to severe	Naming	BDAE (Naming subtest)
5 Khedr et al., 2014	TMS	cortical and subcortical areas	ischemic stroke	non fluent	BDAE, ASRS	mild to severe	Naming	HSS naming score (changes in mean)
6 Tsai et al., 2014	TMS	left hemisphere (not better specified)	ischemic stroke	non fluent	Picture Naming Test, Concise Chinese Aphasia Test	mild to severe	Naming	Object and Action Naming accuracy (%)
7 Wang et al., 2014	TMS	left MCA territory	ischemic stroke	non fluent	Picture Naming Test, Concise Chinese Aphasia Test	NS	Naming	Object and Action Naming accuracy (%)
8 Xue-yan Hu et al., 2018	TMS	left MCA territory	ischemic or hemorrhagic stroke	non fluent	WAB	NS	Naming	WAB- Chinese version (Naming subtest)
9 Fiori et al., 2013	tDCS	left temporal cortex, left temporal-insular region, frontotemporal cortices (for details see Fig. 1 – Fiori et al., 2013 study)	ischemic stroke	non fluent	BADA; Token test	NS	Naming	Mean percentage of response accuracy for nouns and verbs
10 Marangolo et al., 2013 a	tDCS	superior temporal gyrus, frontotemporal cortices and part of the parietal cortex (for details see Fig. 1 – Marangolo et al., 2013 a study)	ischemic stroke	non fluent	BADA	NS	Naming	Mean percentage of correct responses
11 Marangolo et al., 2013 b	tDCS	capsula estrema, claustrum, part of the capsula esterna and putamen, inferior frontal gyrus and superior temporal gyrus (for details see Fig. 1 – Marangolo et al., 2013 b study)	ischemic stroke	non fluent	BADA; Token test	NS	Speech	Mean percentage of correct Content Units
12 Polanowska et al., 2013	tDCS	frontal, temporal, parietal, occipital, insular, subcortical (for details see Table 1 - Polanowska et al., 2013 study)	ischemic stroke	all types	BDAE, ASRS	moderate to severe	Naming	BDAE Naming
13 Shah-Basak et al., 2015	tDCS	left MCA territory, IFG, STG (for details see Table 1 – Shah-Basak et al., 2015study)	stroke	non fluent	WAB	mild to severe	WAB-AQ	Mean WAB-AQ scores
14 Meinzer et al., 2016	tDCS	left MCA territory (for details see Fig. 3 and Table 1 – Meinzer et al., 2016 study)	ischemic or hemorrhage stroke	all types	AAT	NS	Naming	Naming untrained items
15 Spielmann et al., 2018	tDCS	left hemisphere (not better specified)	ischemic or hemorrhage stroke	all types	Shortened token test	mild to severe	Naming	Boston Naming Test
16 Fridriksson et al., 2018	tDCS	left hemisphere (not better specified)	ischemic or hemorrhage stroke	all types	WAB-R	mild to severe	Naming	Change in Correct Naming

Abbreviations: MCA, Middle cerebral artery; IFG, Inferior frontal gyrus; STG, Superior temporal gyrus; AAT, Aachen Aphasic Test; ASRS, Apraxia of Speech Rating Scale; BADA, Battery for the Assessment of Aphasic Deficits; BDAE, Boston Diagnostic Aphasia Examination; BNT, Boston Naming Test; HSS, Hemispheric Stroke Scale; NS, not specified; PALPA, Psycholinguistic assessments of language processing in aphasia; SLTA, Standard Language Test of Aphasia; tDCS, Transcranial direct current stimulation; TMS, transcranial magnetic stimulation; WAB, Western Aphasia Battery; WAB-AQ, WAB Aphasia Quotient; WAB-R, Western Aphasia Battery – Revised.

**Table 3**  
Summary of TMS study characteristics.

Study	Target area(s)	TMS Stimulation Parameters				Number of sessions	Online/Offline Stimulation & Therapy	Sham	Adverse Effects
		rTMS Frequency	Intensity (% RMT)	Number of pulses and duration					
1 Waldowski et al., 2012	Anterior: Broca's homologue	RH(contralateral)	1 HZ inhibitory	90% RMT	1800 pulses (900 PTr; 900 POP), 30 min (15 min PTr; 15 min POP)	15 sessions (5 days × 3 weeks)	offline with speech and language therapy	air-cooled sham coil	no adverse effect related to rTMS
2 Medina et al., 2012	Anterior: pars triangularis (n = 9) or pars orbitalis (n = 1); (best response area between BA 44, BA 45, BA 47)	RH(contralateral)	1 HZ inhibitory	90% RMT	1200 pulses, 20 min	10 sessions (5 days × 2 weeks)	only TMS	coil perpendicular to the scalp	all subjects tolerated stimulation without complaint of physical discomfort or other adverse effects
3 Barwood et al., 2013	Anterior: Broca's homologue (rPTr)	RH(contralateral)	1 HZ inhibitory	90% RMT	1200 pulses, 20 min	10 sessions (5 days × 2 weeks)	only TMS	sham coil	ns
4 Seniów et al., 2013	Anterior: Broca's homologue	RH(contralateral)	1 HZ inhibitory	90% RMT	1800 pulses, 30 min	15 sessions (5 days × 3 weeks)	offline with speech and language therapy	air-cooled sham coil	patients tolerated rTMS well, and no adverse effects were observed
5 Khedr et al., 2014	Anterior: PTr; POP	both *RH (contralateral) and * <i>LH</i> (ipsilateral)	*1 HZ inhibitory ** 20 HZ excitatory	*110% RMT, **80% RMT	* 1000 pulses (500 PTr; 500 POP), **10 trains (5 PTr, 5 POP) of 5 seconds each with an inter-train interval of 30seconds	10 sessions (5 days × 2 weeks)	offline with language therapy	coil rotated at 90° away from the scalp	no patient developed seizures during the study or on follow-up
6 Tsai et al., 2014	Anterior: rPTr	RH(contralateral)	1 HZ inhibitory	90% RMT	600 pulses, 10 min	10 sessions (5 days × 2 weeks)	offline with speech therapy	sham coil	no subjects reported any adverse effects during the study or after the 3-month follow-up
7 Wang et al., 2014	Anterior: rPTr	RH(contralateral)	1 HZ inhibitory	90% RMT	1200 pulses, 20 min	10 sessions (5 days × 2 weeks)	online with picture-naming training	sham coil	one patient in the TMS group reported a dull pain at first when placed under the activated coil, but the discomfort subsided once the stimulation intensity was reduced by 5%
8 Xue-yan Hu et al., 2018 (1 Hz)	Anterior: Broca's homologue	RH(contralateral)	1 HZ inhibitory	80% RMT	600 pulses, 10 min	10 sessions	offline with language therapy	coil rotated at 90° away from the scalp	NS

Abbreviations: BA, Brodmann area; LH, left hemisphere; min, minutes; NS, not specified; POP, pars opercularis; PTr, pars triangularis; rPTr, right pars triangularis; rIFG, right inferior frontal gyrus; RH, right hemisphere; rPOrb, right pars orbitalis; RMT, resting motor threshold; rTMS, repetitive transcranial magnetic stimulation; rSTG, right superior temporal gyrus.

**Table 4**  
Summary of tDCS study characteristics.

ID	Study	tDCS Stimulation Parameters				Reference Electrode	Electrode dimension	Current Intensity	Number of stimulations Duration	Online/Offline Stimulation & Therapy	Sham	Adverse Effects.
		Montage /Bipolar (A-tDCS, C-tDCS)	Stimulation Area, Electrode Position	Reference Electrode	Electrode dimension							
1	Fiori et al., 2013	Unipolar (A-tDCS)	Anterior: anodic (F5-A) Broca's area	LH (ipsilateral)	cathode: contralateral fronto-polar cortex	5 × 7 cm	1 mA, current density = 0.028	20 min, 5 daily sessions	online with naming task	turned off after 30 s	NS	
2	Marangolo et al., 2013a	Unipolar (A-tDCS)	Anterior: anodic (F5-A) Broca's area	LH (ipsilateral)	cathode: contralateral fronto-polar cortex	5 × 7 cm	1 mA, current density = 0.028	20 min, 5 daily sessions	online with naming task	turned off after 30 s	NS	
3	Marangolo et al., 2013b	Unipolar (A-tDCS)	Anterior: anodic (F5-A) Broca's area	LH (ipsilateral)	cathode: contralateral fronto-polar cortex	5 × 7 cm	1 mA, current density = 0.028	20 min, 10 daily sessions	online with conversational therapy	turned off after 30 s	NS	
4	Polanowska et al., 2013	Unipolar (A-tDCS)	Anterior: anodic Broca's area	LH (ipsilateral)	cathode: right supraorbital area	5 × 7 cm	1 mA, current density = 0.028	10 min, 15 daily sessions	offline, language therapy sessions after tDCS	turned off after 15 s	NS	
5	Shah-Basak et al., 2015	Unipolar (A-tDCS or C-tDC to the right or left hemisphere): best response at one of the four active montages (see text) (Phase 1)	Anterior: n = 3: left-frontal anode, n = 3 left-frontal cathode, n = 1 right-frontal cathode	RH or LH (contralateral or ipsilateral)	anode or cathode: contralateral mastoid	5 × 5 cm	2 mA, current density = 0.08	20 min, 10 days sessions	online, picture-naming task	turned off after 1 minute	NS	
6	Meinzer et al., 2016	Unipolar (A-tDCS)	Anterior: anodic left MI	LH (ipsilateral)	cathode: right supraorbital region	anode 5 × 7 cm, cathode 10 × 10 cm	1 mA, current density = 0.028	20 min, 16 sessions in 8 days (2 x 1.5 h/day)	online, computer-assisted naming treatment	turned off after 30 s	Only mild sensations (e.g. itching, tingling, slight burning feeling) during the initial ramping up were reported	
7	Spielmann et al., 2018	Unipolar (A-tDCS)	Anterior: anodic left -IFG	LH (ipsilateral)	cathode: right supraorbital region	5 × 7 cm	1 mA, current density = 0.028	20 min, 10 sessions (2 weeks × 5 days)	online, word-finding therapy	turned off after 30 s	Sixty-nine percent reported no pain (score = 0); the rest reported very little pain/ little pain (score = 1–2), 56% of these participants received sham- tDCS. There was no significant difference in pain rating between groups. Reported side effects were headache and skin irritability; no adverse events were reported during treatment.	
8	Fridriksson et al., 2018	Unipolar (A-tDCS)	Posterior: anodic temporal lobe region with the highest naming-related activation on fMRI	LH (ipsilateral)	cathode: right supraorbital region	5 × 5 cm	1 mA, current density = 0.04	20 min, 15 sessions (3 weeks × 5 days)	online with naming task	turned off after 30 s	Headache – 2 (S-tDCS), Dizziness – 1 (A-tDCS), 2 (S-tDCS), Erythema – 2 (A-tDCS), Convulsion (S-tDCS), Hypertension – 1 (S-tDCS)	

Abbreviations: A-tDCS, anodal transcranial direct current stimulation; C-tDCS, cathodal tDCS; S-tDCS, Sham tDCS; IFG, inferior frontal gyrus; L-IFG, left IFG; R-IFG, right IFG; STG, superior temporal gyrus; R-STG, right STG; L-STG, left STG; MI, primary motor cortex; fMRI, Functional Magnetic Resonance Imaging; LH, left hemisphere; RH, right hemisphere; NS, not specified.

**Table 5a**  
Summary of the TMS studies' characteristics.

N	Study	Study main objective	Study language	Study Arms for the meta-analysis	Follow-up	Results/ Author's Conclusion	Study design	Levels of evidence modified Sackett Scale
1	Waldowski et al., 2012	Effect of Low-Frequency Repetitive Transcranial Magnetic Stimulation on Naming Abilities in Early-Stroke Aphasic Patients: A Prospective, Randomized, Double-Blind Sham-Controlled Study	Polish	TMS VS sham	15 weeks	all groups improved but there was no significant difference in average test scores between groups at any time point	RCT	Level 1b
2	Medina et al., 2012	Finding the Right Words: Transcranial Magnetic Stimulation Improves Discourse Productivity in Non-fluent Aphasia After Stroke	English	TMS VS sham	2 months	trends toward greater changes from baseline in subjects receiving rTMS compared to sham (low statistical power)	Randomized, Crossover (2 months intersession interval)	Level 1b
3	Barwood et al., 2013	Long term language recovery subsequent to low frequency rTMS in chronic non-fluent aphasia	English	TMS VS sham	1 week, 2 months, 8 months, 12 months	rTMS > Sham for naming, expressive language and auditory comprehension	RCT	Level 1b
4	Seniów et al., 2013	Transcranial Magnetic Stimulation Combined with Speech and Language Training in Early Aphasia Rehabilitation: A Randomized Double-Blind Controlled Pilot Study	Polish	TMS VS sham	15 weeks	rTMS was not effective for all post-stroke aphasia patients, although it might benefit selected patients	RCT	Level 1b
5	Khedr et al., 2014	Dual-Hemisphere Repetitive Transcranial Magnetic Stimulation for Rehabilitation of Post-stroke Aphasia: A Randomized, Double-Blind Clinical Trial	Egyptian	TMS VS sham	1 month, 2 months	greater improvement in the language scores after real rTMS compared with sham rTMS	RCT	Level 1b
6	Tsai et al., 2014	The Persistent and Broadly Modulating Effect of Inhibitory rTMS in Non-fluent Aphasic Patients: A Sham-Controlled, Double-Blind Study	Mandarin Chinese	TMS VS sham	3 months	inhibition of the contralesional pars triangularis enhances language recovery	RCT	Level 1b
7	Wang et al., 2014	Efficacy of Synchronous Verbal Training During Repetitive Transcranial Magnetic Stimulation in Patients With Chronic Aphasia	Chinese	TMS VS sham	3 months	rTMS and language training can be combined to achieve outcomes superior to those obtained when used separately	RCT	Level 1b
8	Xue-yan Hu et al., 2018 (HZ)	Effects of different frequencies of repetitive transcranial magnetic stimulation in stroke patients with non-fluent aphasia: a randomized, sham-controlled study	Chinese	LF-TMS VS sham	2 months	LF-rTMS and HF-rTMS are both beneficial to the recovery of linguistic function in patients with post-stroke non-fluent aphasia	RCT	Level 1b

**Table 5b**  
Summary of the tDCS studies' characteristics.

N	Study	Study main objective	Study language	Study Arms for the meta-analysis	Follow-up	Results/ Author's Conclusion	Study design	Levels of evidence (PEDro)
9	Fiori et al., 2013 (Broca)	tDCS stimulation segregates words in the brain: evidence from aphasia	Italian	Broca tDCS VS sham	1 week, 4 weeks	greater improvement in object naming after tDCS	Randomized Crossover (6 days of intersession interval)	Level 2
10	Marangolo et al. 2013 a (Broca)	Differential involvement of the left frontal and temporal regions in verb naming: A tDCS treatment study	Italian	Broca tDCS VS sham	2 weeks, 4 weeks	better response accuracy during the anodic tDCS over Broca's area VS tDCS over Wernicke or VS Sham	Randomized Crossover (6 days of intersession interval)	Level 2
11	Marangolo et al. 2013 b (Broca)	tDCS over the left inferior frontal cortex improves speech production in aphasia	Italian	Broca tDCS VS sham	4 weeks	anodic tDCS over Broca's area together with intensive "Conversational Therapy" improves informative speech	Randomized Crossover (14 days of intersession interval)	Level 2
12	Polanowska et al., 2013	No effects of anodal transcranial direct stimulation on language abilities in early rehabilitation of post-stroke aphasic patients	Polish	Broca tDCS VS sham	3 months	the results did not confirm a positive impact of repeated A-tDCS, preceding language therapy, on language abilities	RCT	Level 1b
13	Shah-Basak et al., 2015	Individualized treatment with transcranial direct current stimulation in patients with chronic non-fluent aphasia due to stroke	English	Broca tDCS VS sham	2 weeks, 2 months	individualized tDCS treatment enhance aphasia recovery	Randomized Partial Crossover (2 months of intersession interval)	Level 2
14	Meinzer et al., 2016	Electrical stimulation of the motor cortex enhances treatment outcome in post-stroke aphasia	German	M1 A-tDCS VS sham	6 months	better results for untrained items in the A-tDCS group	RCT	Level 1b
15	Spielmann et al., 2018	Transcranial Direct Current Stimulation Does Not Improve Language Outcome in Subacute Post-stroke Aphasia	Dutch	left IFG tDCS VS sham	10 weeks, 6 months	results do not support an effect of tDCS as an adjuvant treatment in subacute post stroke aphasia	RCT	Level 1b
16	Fridriksson et al., 2018	Transcranial Direct Current Stimulation vs Sham Stimulation to Treat Aphasia After Stroke A Randomized Clinical Trial	English	A-tDCS VS Sham	4 weeks, 24 weeks	anodal tDCS during speech therapy is feasible and potentially transformative for aphasia treatment	RCT	Level 1b

Abbreviations: M1, primary motor cortex; A-tDCS, anodal transcranial direct current stimulation; rTMS, repetitive transcranial magnetic stimulation; IFG, inferior frontal gyrus; LF, low frequency; HF, high frequency; RCT, Randomized controlled trial; PEDro, the Physiotherapy Evidence Database tool.  
NOTE: in bold the follow up period that was included into the meta-analysis.

**Table 6a**  
Summary of the Physiotherapy Evidence Database (PEDro) TMS studies.

PEDro	Publication	Waldowski et al., 2012	Medina et al., 2012	Barwood et al., 2013	Sentiów et al., 2013	Khedr et al., 2014	Tsai et al., 2014	Wang et al., 2014	Xue-yan Hu et al., 2018 (1 Hz)
		RCT	Randomised	Crossover	RCT	RCT	RCT	RCT	RCT
NO = 0, Yes = 1		1	1	1	1	1	1	1	1
1. eligibility criteria were specified: no yes where:		1	1	1	1	1	1	1	1
2. subjects were randomly allocated to groups: no yes where:		0	0	0	0	0	0	0	0
3. allocation was concealed: no yes where:		1	1	1	1	1	1	1	1
4. the groups were similar at baseline regarding the most important prognostic indicators: no yes where:		1	1	1	1	1	1	1	1
5. there was blinding of all subjects no: yes where:		1	1	1	1	1	1	1	1
6. there was blinding of all therapists who administered the therapy: no yes where:		1	1	1	1	1	1	1	1
7. there was blinding of all assessors who measured at least one key outcome: no yes where:		1	1	1	1	1	1	1	1
8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups: no yes where:		1	1	1	1	1	1	1	1
9. all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analyzed by "intention to treat": no yes where:		1	1	1	1	1	1	1	1
10. the results of between-group statistical comparisons are reported for at least one key outcome: no yes where:		1	1	1	1	1	1	1	1
11. the study provides both point measures and measures of variability for at least one key outcome: no yes where:		1	1	1	1	1	1	1	1
Total		9	9	9	9	9	9	9	9

identify other relevant trials we checked the reference lists of the included studies and previous meta-analysis and relevant reviews. Uncertainties regarding some inclusion were solved by the authors through discussion.

2.2. Data extraction

For each included paper, the relevant information to be extracted regarded:

- i) the patients' characteristics: the sample size (treatment and control group), gender, age, time since stroke (chronic/ subacute), handedness, dropouts (Table 1);
- ii) disorders' characteristics: lesion area, lesion type, aphasia diagnosis and instruments used for evaluation of the disorder, aphasia severity, outcome evaluation (Table 2);
- iii) rTMS stimulation protocol: target area(s), rTMS frequency and intensity, number of pulses and duration, number of sessions, online or offline stimulation and associated therapy (if any), sham, adverse effects (Table 3);
- iv) tDCS stimulation protocol: montage type (unipolar or bipolar, cathodic or anodic), electrode dimension, stimulation area, electrode position, stimulation hemisphere, reference electrode, current intensity, number of stimulations and duration, online vs offline stimulation and associated therapy (if any), sham, tDCS adverse effects (Table 4);
- v) characteristics of the study: main objective, study design, language of the study, study arms, follow-up results and authors' conclusion, level of evidence on PEDro's scale (Tables 5a and 5b);

Means, standard deviations, sample size for experimental and control conditions were extracted. Across studies, aphasia assessment and outcome measures were heterogeneous, but for the purpose of this meta-analysis, only continuous aphasia measurements were chosen, namely, the primary outcome was based on picture naming accuracy or, if not reported, the explicitly declared primary outcome (e.g., aphasia battery results, reaction times, speech content units). When adequate information was not provided in the results description, means and standard deviations or standard errors were extracted from published figures using WebPlotDigitizer (<https://automeris.io/WebPlotDigitizer/>). Data analysis, standardized mean difference (SMD), sampling variance and summary analyses were computed for each included study, using the "metafor package" for R (version 3.4.3) (Viechtbauer, 2010). Hedges' g (computed as the difference between the mean of the experimental condition and the mean of the control condition, divided by the pooled standard deviation) was chosen for the effect size, instead of Cohen's d, because due to low sample sizes across most of the studies, we considered it more adequate for our analysis: indeed, many researches included only seven/twelve participants (DeVellis, 1991; Faraone, 2008). If only standard errors were reported, we converted them into standard deviations (SD) using the formula  $SD = SE \sqrt{n}$ ; SE = standard errors, n = number of participants (DeVellis, 1991); if this method of data extraction could not be applied, the missing information was requested from the corresponding author.

For each effect, we included moderator variables related to: i) stimulation type (rTMS or tDCS), ii) time points (after treatment or at follow-up), iii) study design (crossover or RCTs), iv) time from the symptom onset (chronic or subacute).

In order to avoid entering multiple data points from the same study into the meta-analysis, results from a single experiment were aggregated to obtain a single measure per experiment. If several time points or control conditions were reported (e.g., comparing cathodal and anodal stimulation, or different brain regions stimulation within the same patients), data were extracted using the following criteria:

- from each study we chose one follow-up time point only,

**Table 6b**  
Summary of the Physiotherapy Evidence Database (PEDro) tDCS studies.

	Publication									
	Fiori et al., 2013 (Broca) Randomised Crossover	Marangolo et al. 2013 a (Broca) Randomised Crossover	Marangolo et al. 2013 b (Broca) Randomised Crossover	Polanowska et al., 2013 RCT	Shah-Basak et al., 2015 Randomised Partial Crossover	Meinzer et al., 2016 RCT	Spielmann et al., 2018 RCT	Fridriksson et al., 2018 RCT		
1. eligibility criteria were specified: no yes where:	1	1	1	1	1	1	1	1	1	1
2. subjects were randomly allocated to groups: no yes where:	1	1	1	1	1	1	1	1	1	1
3. allocation was concealed: no yes where:	0	0	0	0	0	0	0	0	0	0
4. the groups were similar at baseline regarding the most important prognostic indicators: no yes where:	1	1	1	1	1	1	1	1	1	1
5. there was blinding of all subjects: no yes where:	1	1	1	1	1	1	1	1	1	1
6. there was blinding of all therapists who administered the therapy: no yes where:	1	0	1	1	1	1	1	1	1	1
7. there was blinding of all assessors who measured at least one key outcome: no yes where:	0	0	0	1	0	1	1	1	1	0
8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups: no yes where:	1	1	1	0	1	1	1	1	1	1
9. all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome were analyzed by "intention to treat": no yes where:	1	1	1	1	1	1	1	1	1	1
10. the results of between-group statistical comparisons are reported for at least one key outcome: no yes where:	0	0	0	1	1	1	1	1	1	1
11. the study provides both point measures and measures of variability for at least one key outcome: no yes where:	0	0	0	1	1	1	1	1	1	1
Total	6	5	6	8	8	9	9	9	9	9

**Table 7a**  
Risk of bias, TMS studies.

	Waldowski et al., 2012 RCT	Medina et al., 2012 Randomized Crossover	Barwood et al., 2013 RCT	Seniów et al., 2013 RCT	Khedr et al., 2014 RCT	Tsai et al., 2014 RCT	Wang et al., 2014 RCT	Xue-yan Hu et al., 2018 (1 Hz) RCT
Yes = 1 No = 0								
Was random sequence generation used (i.e. no potential for selection bias)?	1	1 NS <sup>a</sup>	1	1	1	1	1	1 NS <sup>a</sup>
Was allocation concealment used (i.e. no potential for selection bias)?	0	0	0	1	1	1	1	0
Was there blinding of participants and personnel (i.e. no potential for performance bias)?	1	1	1	1	1	1	1	0
Was there blinding of outcome assessment (i.e. no potential for detection bias)?	1	1	1	1	1	1	1	0
Was an objective outcome used?	1	1	1	1	1	1	1	1
Were more than (80%) of participants enrolled in trials included in the analysis? (i.e. no potential attrition bias)	1	1	1	1	1	1	1	1
Were data reported consistently for the outcome of interest (i.e. no potential selective reporting)? (no potential reporting bias)	1	1	1	1	1	1	1	1
No other biases reported? (no potential of other bias)	1	1	1	1	1	1	1	0
Did the trials end as scheduled (i.e. not stopped early)?	1	1	1	1	1	1	1	1
TOTAL	8	8	8	9	9	9	9	5

NOTE.

<sup>a</sup> randomization was used but the method of randomization is not specified.

specifically, the one that represented the longest follow-up period matching the follow-up time points reported by the other studies included in the meta-analysis;

- only data regarding treatment effects on language recovery were extracted (e.g., aphasia battery scores, speech, etc.); fMRI data, blood flow or other parameters used as indicators of treatment effects were excluded;
- from each study, since often different stimulation protocols were tested, we chose one type only (e.g. montage, stimulation intensity), namely, the one that the authors considered as potentially effective, or, in the absence of such information, the type most frequently applied in the literature. This was done in order to reduce variability among the included studies;
- based on previous meta-analyses, and in order to reduce variability among studies, the preferred outcome was naming accuracy; in the absence of this measure we used a different outcome, e.g., the total score from the aphasia battery, speech content units, etc.;
- if a study reported different outcome measures for the same treatment (e.g., accuracy but also reaction times) we chose naming accuracy, the most frequently reported outcome in the included studies.

2.3. Study quality assessment

Methodological quality of the included studies was assessed using the Physiotherapy Evidence Database (PEDro) tool and a grade for the level of evidence was assigned to each study according to the modified Sackett Scale (Tables 5a and 5b for the level of evidence) (Moseley et al., 2002; Sackett et al., 2000).

PEDro is an eleven yes/no item scale (see Tables 6a and 6b) assessing the quality of clinical trials, which is considered a valid and comprehensive instrument previously applied in systematic reviews (McIntyre et al., 2016). Items can be scored as either present (1) or absent (0) and the total score is obtained by summation, with higher values indicating greater quality: 9–10: excellent; 6–8: very good; 4–5: good; < 4: poor (Foley et al., 2003).

The Sackett Scale includes five levels of evidence: Level 1 comprises high quality RCTs (PEDro ≥ 6) and meta-analysis, being divided into level 1a and level 1b, based on the number of RCTs. Level 2 evidence is also derived from RCTs but with a PEDro score < 6. Level 3 evidence refers to non-randomized clinical trials and case controls designs (retrospective studies comparing conditions including historical controls). Level 4 and 5 refer to case series, uncontrolled pre- post-treatment tests, observational studies, and case report designs.

Overall evidence was qualified using the grading of recommendations, assessment, development and evaluations (GRADEpro GDT, <https://gradepro.org>) and the Meader et al.’s (2014) GRADE assessment checklist. GRADE provides a transparent approach and guidance on rating the overall quality of research evidence indicating four levels of evidence along a continuum (high, moderate, low, and very low) based on five factors: 1. risk of bias, 2. inconsistency, 3. indirectness, 4. imprecision, 5. publication bias. The risk of bias for each included study was evaluated using the simplified GRADE checklist proposed by Meader et al. (2014), based on the Cochrane risk of bias tool items (Tables 7a and 7b).

For each meta-analysis pool effect, the level of heterogeneity, by means of the Q and I<sup>2</sup> statistics was calculated (Higgins and Thompson, 2002). Q estimates the amount of variation due to sampling error, while I<sup>2</sup> evaluates which proportion of the observed variance reflects a real difference in effect sizes (I<sup>2</sup> values of 25%, 50%, and 75% have been interpreted as representing small, moderate and high levels of heterogeneity, respectively). Influential cases were identified using the “inf” function from the “metafor package” for R (Polanin et al., 2016; Kovalchik, 2013; Del Re, 2015).

Meta-analysis publication bias may be due to many factors like the fact that we explicitly included only peer-reviewed, English-written

**Table 7b**  
Risk of bias, tDCS studies.

	Fiori et al., 2013 (Broca) Randomised Crossover	Marangolo et al. 2013 a (Broca) Randomised Crossover	Marangolo et al. 2013 b (Broca) Randomised Crossover	Polanowska et al., 2013 RCT	Shah-Basak et al., 2015 Randomised Partial Crossover	Meinzer et al., 2016 RCT	Spielmann et al., 2018 RCT	Fridriksson et al., 2018 RCT
Yes = 1 No = 0								
Was random sequence generation used (i.e. no potential for selection bias)?	1 NS <sup>b</sup>	1 NS <sup>b</sup>	1	1 NS <sup>b</sup>	1 NS <sup>b</sup>	1	1 NS <sup>b</sup>	1
Was allocation concealment used (i.e. no potential for selection bias)?	0	0	0	1	0	0	0	0
Was there blinding of participants and personnel (i.e. no potential for performance bias)?	1	0	1	1	0	1	1	1
Was there blinding of outcome assessment (i.e. no potential for detection bias)?	0	0	0	1	0	0	1	0
Was an objective outcome used?	1	1	1	1	1	1	1	1
Were more than (80%) a of participants enrolled in trials included in the analysis? (i.e. no potential attrition bias)	1	1	1	1	0	1	1	1
Were data reported consistently for the outcome of interest (i.e. no potential selective reporting)? (no potential reporting bias)	1	1	1	1	1	1	1	1
No other biases reported? (no potential of other bias) <sup>a</sup>	0	0	0	1	0	0	1	1
Did the trials end as scheduled (i.e. not stopped earlier)?	1	1	1	1	1	1	1	1
TOTAL	6	5	6	9	4	6	8	7

NOTE.

<sup>a</sup> carry over effect in crossover studies.

<sup>b</sup> randomization was used but the method of randomization is not specified.

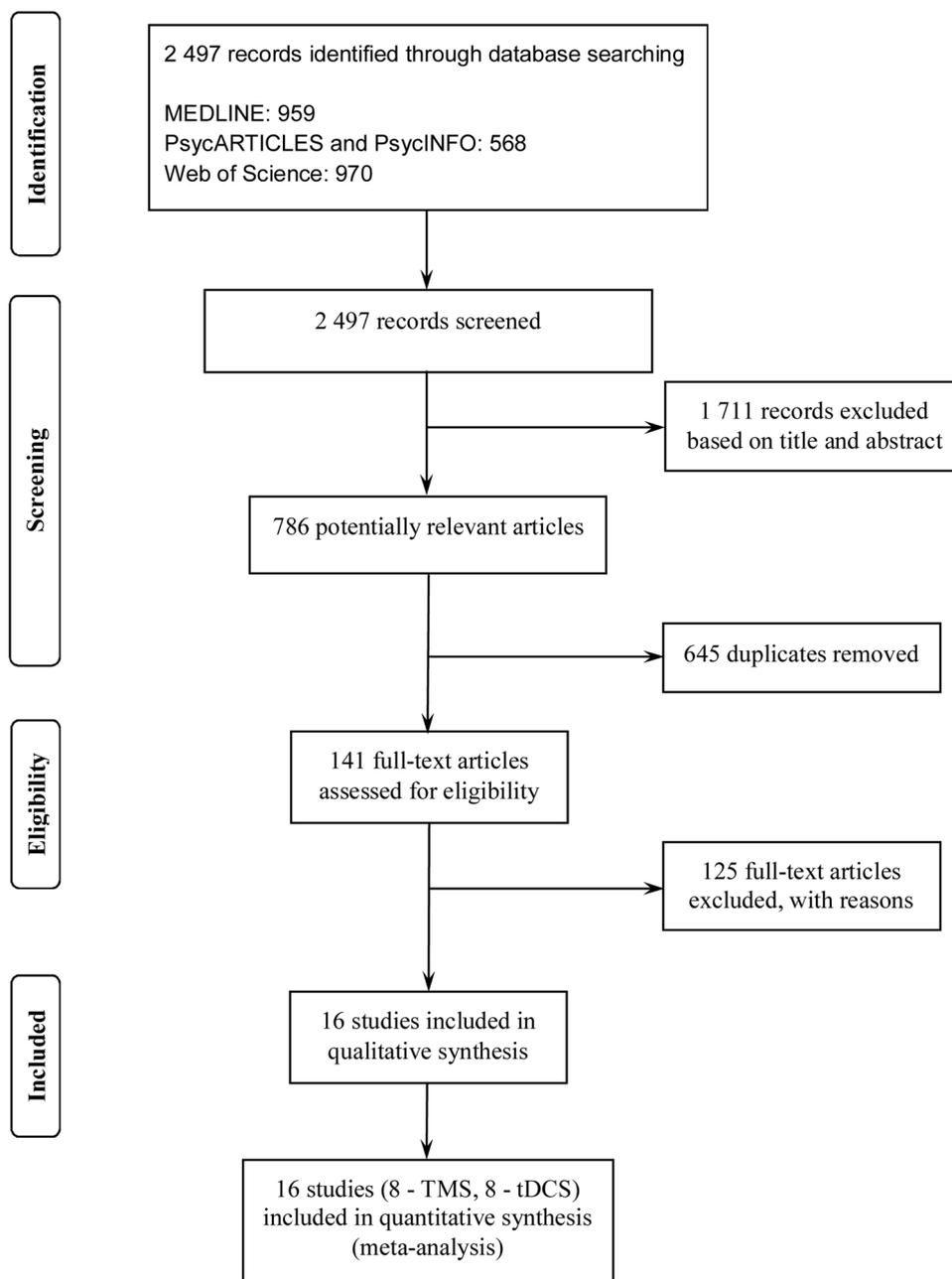


Fig. 1. Flow Diagram of study selection and inclusion.

papers or that studies with stronger effects sizes are more likely to be published. Publication bias was assessed using the funnel plot tool together with the Egger's regression test (Egger et al., 1997) and the rank correlation test (Begg and Mazumdar, 1994). The trim and fill method (which imputes "missing" studies to create a more symmetrical funnel plot) (Duval and Tweedie, 2000) was used for bias correction only if the previously mentioned tests were significant, since a  $p$  value  $< 0.05$  is consistent with a non-symmetrical funnel plot.

### 3. Results

The literature search initially retrieved 2497 publications and, following application of the eligibility criteria and duplicates removal, 141 studies were selected for a full text review; in the end, sixteen studies met the inclusion criteria. Fig. 1 summarizes the inclusion process.

#### 3.1. Studies characteristics

Eight studies used tDCS as a therapeutic application for aphasia treatment: four randomized controlled trials (RCT) (Polanowska et al., 2013; Meinzer et al., 2016; Spielmann et al., 2018; Fridriksson et al., 2018), three randomized crossover studies (Fiori et al., 2013; Marangolo et al., 2013a; Marangolo et al., 2013b), one partial randomized crossover study (Shah-Basak et al., 2015) (Table 5b). Eight studies investigated the effects of rTMS on aphasic patients after stroke: seven were RCTs (Naeser et al., 2005; Waldowski et al., 2012; Barwood et al., 2013; Seniów et al., 2013; Khedr et al., 2014; Tsai et al., 2014; Wang et al., 2014; Hu et al., 2018) and one was a randomized partial crossover (Medina et al., 2012) (Table 5a). The majority of these studies used a combined therapy, namely noninvasive brain stimulation was associated with language training online (behavioral treatment during the stimulation) or offline (taking advantage of the stimulation after effects, the linguistic training was delivered after neurostimulation);

**Table 8**  
Summary of the meta-analysis results.

Comparison	Number of Studies	Effect Size Summary	95% CI	Z	p-value for Z	Q – Test for Heterogeneity	p-value for Q	I <sup>2</sup> : total heterogeneity	Influence Test	Regression Test for Funnel Plot Asymmetry	Rank Correlation Test for Funnel Plot Asymmetry (Kendall's tau)
<b>tDCS vs. TMS at follow-up</b>											
Test of Moderators: QM(1) = 3.376, p = 0.066											
Overall NIBS Follow up	16	0.53	0.2998, 0.7511	4.56	< .0001	17.33	0.29	24.78%	none	z = 1.3460, p = 0.1783	tau = 0.1333, p = 0.5056
TMS only Follow-up	8	0.71	0.4295, 0.9966	4.92	< .0001	5.94	0.55	3.54%	Tsai et al., 2014	z = 0.6874, p = 0.4918	tau = 0, p = 1.0
tDCS only Follow-up	8	0.33	0.0319, 0.6249	2.17	0.02	7.15	0.41	18.32%	Spielmann et al., 2018	z = 0.9908, p = 0.3218	tau = 0.2857, p = 0.3988
<b>After vs. Follow-up (Overall NIBS)</b>											
paired t-test: t (14) = -1.15, p = 0.26; 99% CI = [-0.23, 0.10]											
Overall NIBS After	15	0.48	0.2623, 0.7015	4.30	< .0001	15.2	0.37	20.33%	Spielmann et al., 2018	z = 1.0746, p = 0.2826	tau = 0.1810, p = 0.3795
<b>TMS at follow-up vs. TMS immediately after</b>											
paired t-test: t (6) = -0.54, p = 0.24; 99% CI = [-0.54, 0.24]											
TMS only After	7	0.66	0.3738, 0.9450	4.52	< .0001	3.16	0.79	0.00%	none	z = -0.2133, p = 0.8311	tau = 0.1439, p = 0.7726
<b>tDCS at follow-up vs. tDCS immediately after</b>											
paired t-test: t (7) = 0.14, p = 0.88; 99% CI = [-0.16, 0.17]											
tDCS only After	8	0.34	0.0231, 0.6522	2.1	0.0354	8.73	0.27	26.14%	Spielmann et al., 2018; Marangolo et al. 2013b	z = 1.0851, p = 0.2779	tau = 0.2857, p = 0.3988
<b>tDCS vs. TMS RCTs follow-up</b>											
Test of Moderators: QM(1) = 5.616, p = 0.018											
RCTs Overall	12	0.50	0.2407, 0.7512	3.81	p = 0.0001	15.6	0.16	33.14%	none	z = 1.3544, p = 0.1756	tau = 0.2424, p = 0.3108
RCT TMS	8	0.71	0.4295, 0.9966	4.93	< .0001	5.94	0.55	3.54%	Tsai et al., 2014	z = 0.6874, p = 0.4918	tau = 0.00, p = 1.0
RCT tDCS	4	0.18	-0.1556, 0.5175	1.05	0.29	2.64	0.45	21.70%	Spielmann et al., 2018; Fridriksson et al., 2018	z = -0.1602, p = 0.8728	tau = 0.0000, p = 1.0000
<b>Chronic: TMS vs. tDCS</b>											
Test of Moderators: QM(1) = 0.203, p = 0.652											
Chronic Overall	11	0.57	0.3302, 0.8143	4.163	< .0001	4.74	0.90	0.00%	none	z = 0.5442, 0.5863	tau = 0.0545, p = 0.8793
Chronic TMS	5	0.62	0.2524, 0.9884	3.30	0.001	2.71	0.60	2.54%	Wang et al., 2014 and Tsai et al., 2014	z = 0.3986, p = 0.6902	tau = -0.2, p = 0.8167
Chronic tDCS	6	0.54	0.2092, 0.8624	3.21	0.0013	1.92	0.8594	0.00%	Fridriksson et al., 2018	z = 0.2920, p = 0.7703	tau = 0.3333, p = 0.4694
<b>Subacute</b>											
Subacute Overall	5	0.48	-0.0465, 0.9976	1.79	0.07	11.6	0.02	65.82%	Khedr et al., 2014 and Spielmann et al., 2018	z = 3.0079, p = 0.0026	tau = 0.8000, p = 0.0833
Subacute TMS	3	0.85	0.3773, 1.3215	3.53	0.0004	2.62	0.27	15.19%	Waldowski et al., 2012; Khedr et al., 2014	z = 0.7712, p = 0.4406	tau = 0.3333, p = 1.0000

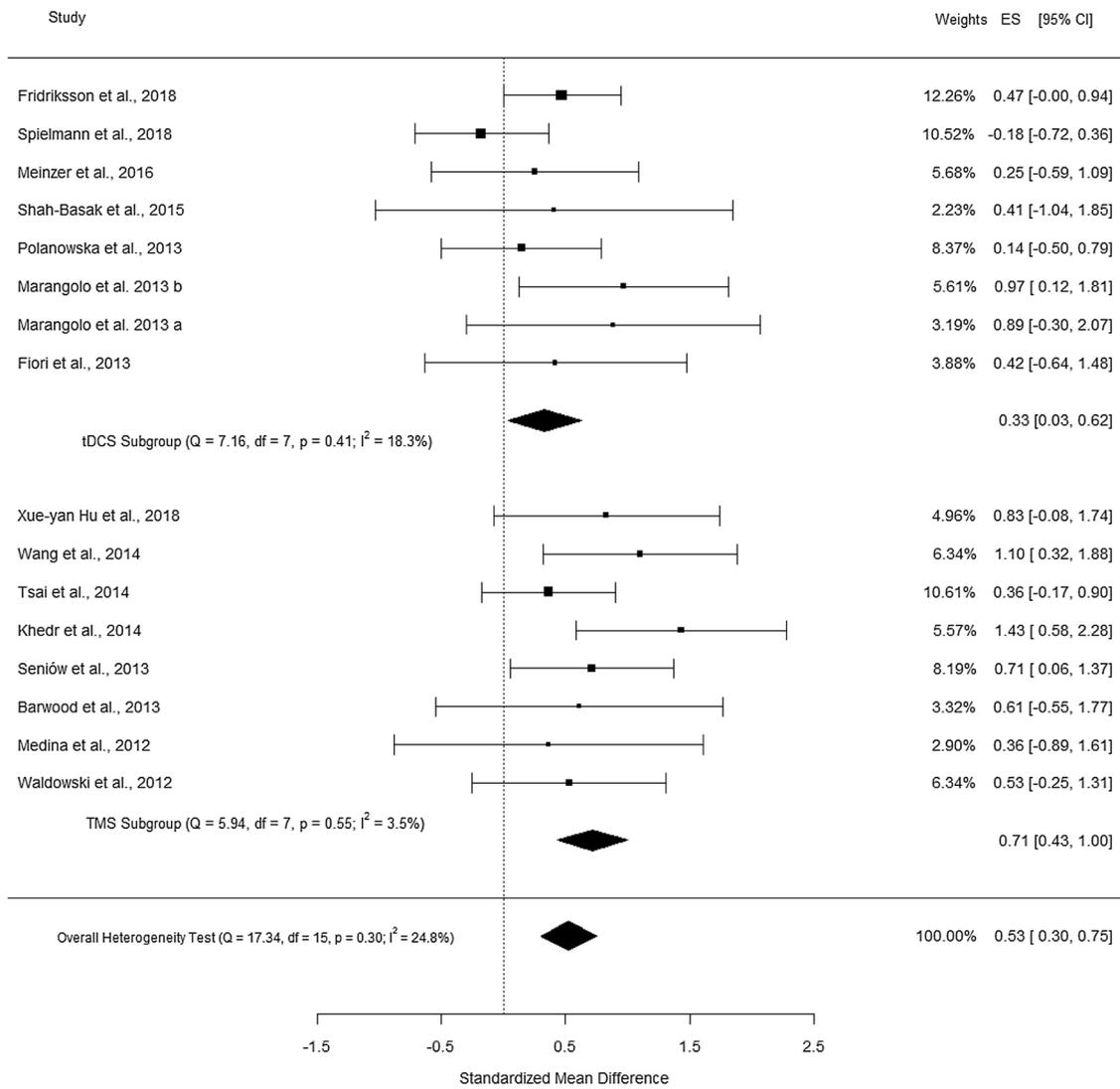


Fig. 2. Forest plot of effect sizes, broken down by NIBS (TMS vs. tDCS), at follow-up.

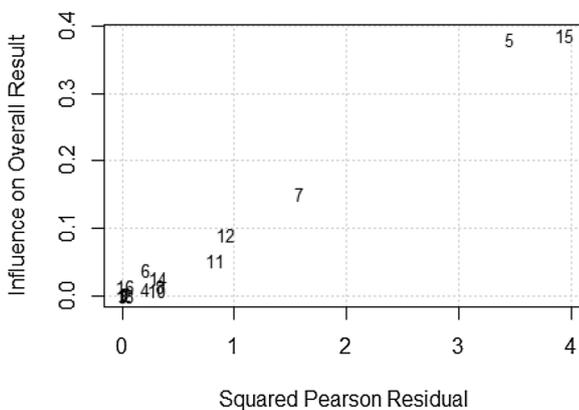


Fig. 2.1.0. Baujat plot at follow-up (TMS & tDCS).

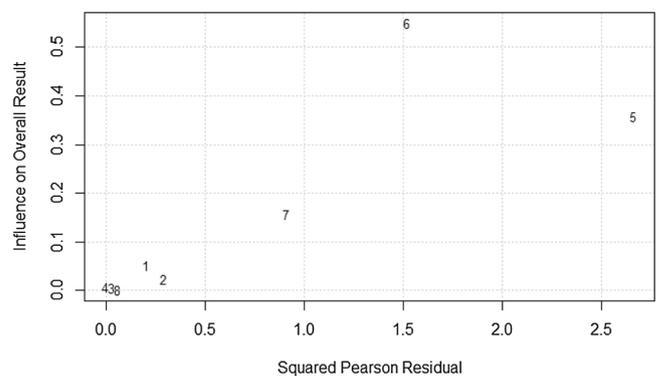


Fig. 2.1.1. Baujat plot at follow-up (TMS only).

only two rTMS studies, (Barwood et al., 2013; Medina et al., 2012), used neurostimulation as a monotherapy.

The methodological quality of the eleven RCTs, according to the modified Sackett Scale, was good, scoring between 6 and 10 on the PEDro scale (level 1b evidence). Four studies had randomized crossover designs, while one had a partial crossover design (Shah-Basak et al., 2015) and their scores ranged between 4 and 9 (evidence level 1b and

2). The main risk of bias was the lack of allocation concealment and the carry over effect due to a very short washout period before the groups were switched to the other experimental arm; for instance, in the Fiori et al. (2013) study, the intersession interval (between treatment and sham) was of only 6 days. Overall, the level of evidence ranged from good (level 2–4 studies) to very good (level 1b – 12 studies).

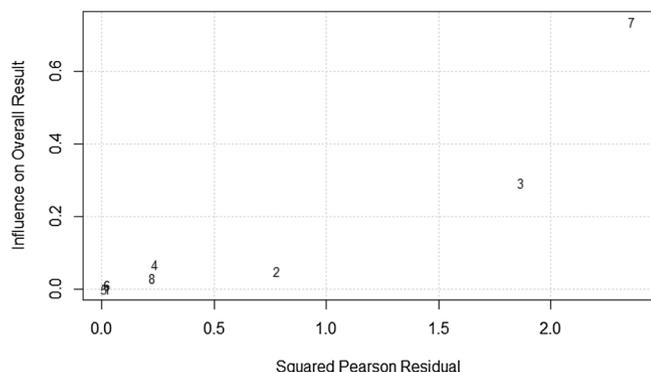


Fig. 2.1.2. Baujat plot at follow-up (tDCS only).

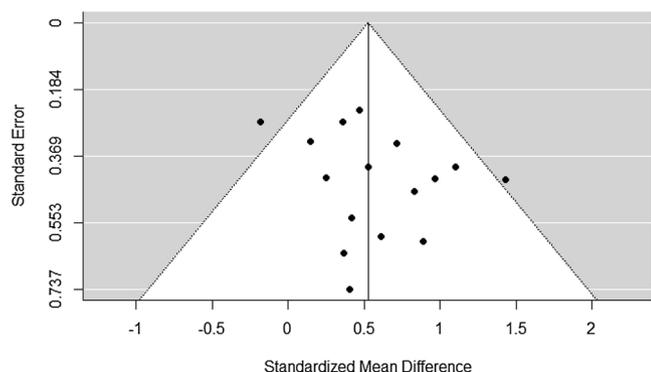


Fig. 2.2.0. Publication bias assessed by the funnel plot at follow-up (TMS & tDCS).

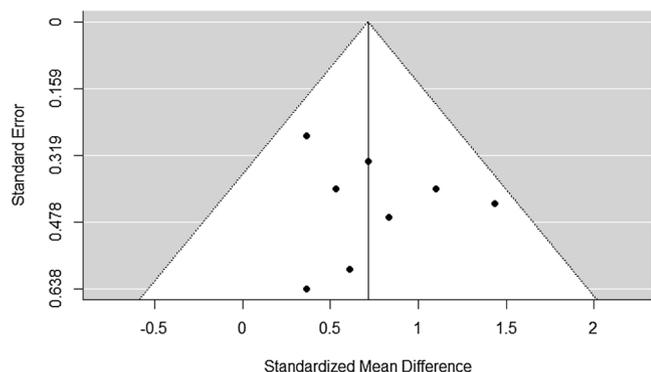


Fig. 2.2.1. Publication bias assessed by trim and fill funnel plot at follow-up (TMS only).

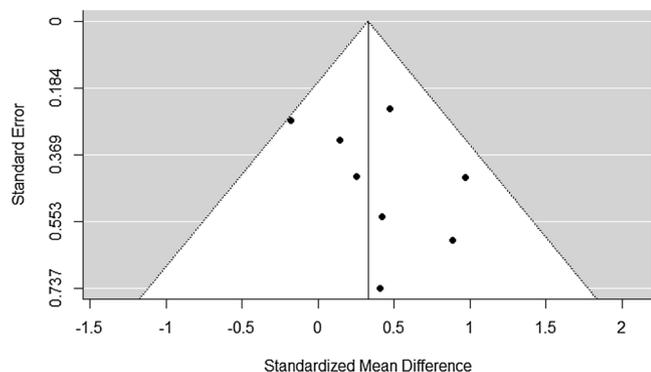


Fig. 2.2.2. Publication bias at follow-up assessed by funnel plot (tDCS only).

### 3.2. Participants' characteristics

The review included twenty studies involving 439 stroke patients diagnosed with aphasia (208 in the experimental condition, 202 in the sham condition and 29 in both experimental arms as part of crossover designs); 217 received rTMS stimulation (118 real rTMS and 99 sham) and 222 participated in tDCS experiments (90 real tDCS, 103 sham and 29 both conditions).

Participants' characteristics were heterogeneous among studies (Table 1), especially regarding:

- **time interval from stroke** – five papers focused on patients in a subacute stage (N = 184) ranging from 10 to 187 days post-stroke (Polanowska et al., 2013; Spielmann et al., 2018; Waldowski et al., 2012; Seniów et al., 2013; Khedr et al., 2014), while all the others included only participants with chronic aphasia (N = 255), the post-stroke interval ranging from 7 months to 9 years;
- **aphasia diagnosis** – this was obtained by means of different tests and aphasia batteries based on different approaches (neurolinguistics vs. psycholinguistics), the most frequent ones being: the Boston Diagnostic Aphasia Examination (BDAE), the Boston Naming Test (BNT), Psycholinguistic Assessment of Language Processing in Aphasia (PALPA), Aachen Aphasia Test (AAT), Aphasia Severity Rating Scale (ASRS) and the Western Aphasia Battery (WAB); then studies explicitly selected participants with non-fluent aphasia while 6 studies included all types of aphasia (Table 2);
- participants' **age** ranged between 37 and 77 years (Table 1),
- **lesion** – only left hemisphere stroke patients were selected but only general information about lesion site, extension, etiology were provided, with the exception of a few cases for which more details were reported, including MRI scans (Fiori et al., 2013).

### 3.3. Intervention

#### 3.3.1. Target area

The target area was identified in different brain regions depending on the experimental hypothesis and the stimulation type.

All rTMS studies, with one exception - Khedr et al. (2014) that stimulated both hemispheres, stimulated anterior language areas (pars triangularis or pars opercularis) on the contralesional (right) hemisphere.

The most commonly targeted brain region in tDCS experiments was Broca's area, only in one paper (Shah-Basak et al., 2015) a personalized approach was used: based on pre-treatment tDCS assessment sessions with different montages, the authors chose which area to target, namely anterior or posterior, contralesional or ipsilesional. Fridriksson et al. (2018) chose the temporal lobe region with the highest naming related activation during fMRI, while Meinzer et al. (2016) tested the effectiveness of M1 (primary motor cortex) stimulation on language rehabilitation.

#### 3.3.2. Stimulation protocol: rTMS

All of the included studies used an inhibitory stimulation protocol, with the exception of Khedr et al. (2014) that applied a dual-hemisphere stimulation (excitatory, 20 Hz over Broca's area and inhibitory over the right, unaffected homologous of Broca's area), rTMS was delivered at an intensity between 110% and 80% of the resting motor threshold (7 out of 8 studies used a 90% RMT intensity) at a frequency of 1 Hz for a duration ranging between 10 min and 30 min for a total of 10/15 sessions (Table 3). Magnetic pulses were delivered with figure of eight shaped coils.

**Stimulation protocol: tDCS.** In all of the included studies, tDCS was bipolar and in general two equal sized electrodes were used; only Meinzer et al. (2016) selected different dimensions: anode 5 × 7 cm, cathode 10 × 10 cm. Each electrode had an area of 25 cm<sup>2</sup> (5 cm × 5 cm) or in some cases 35 cm<sup>2</sup> (5 cm × 7 cm), and with a few exceptions

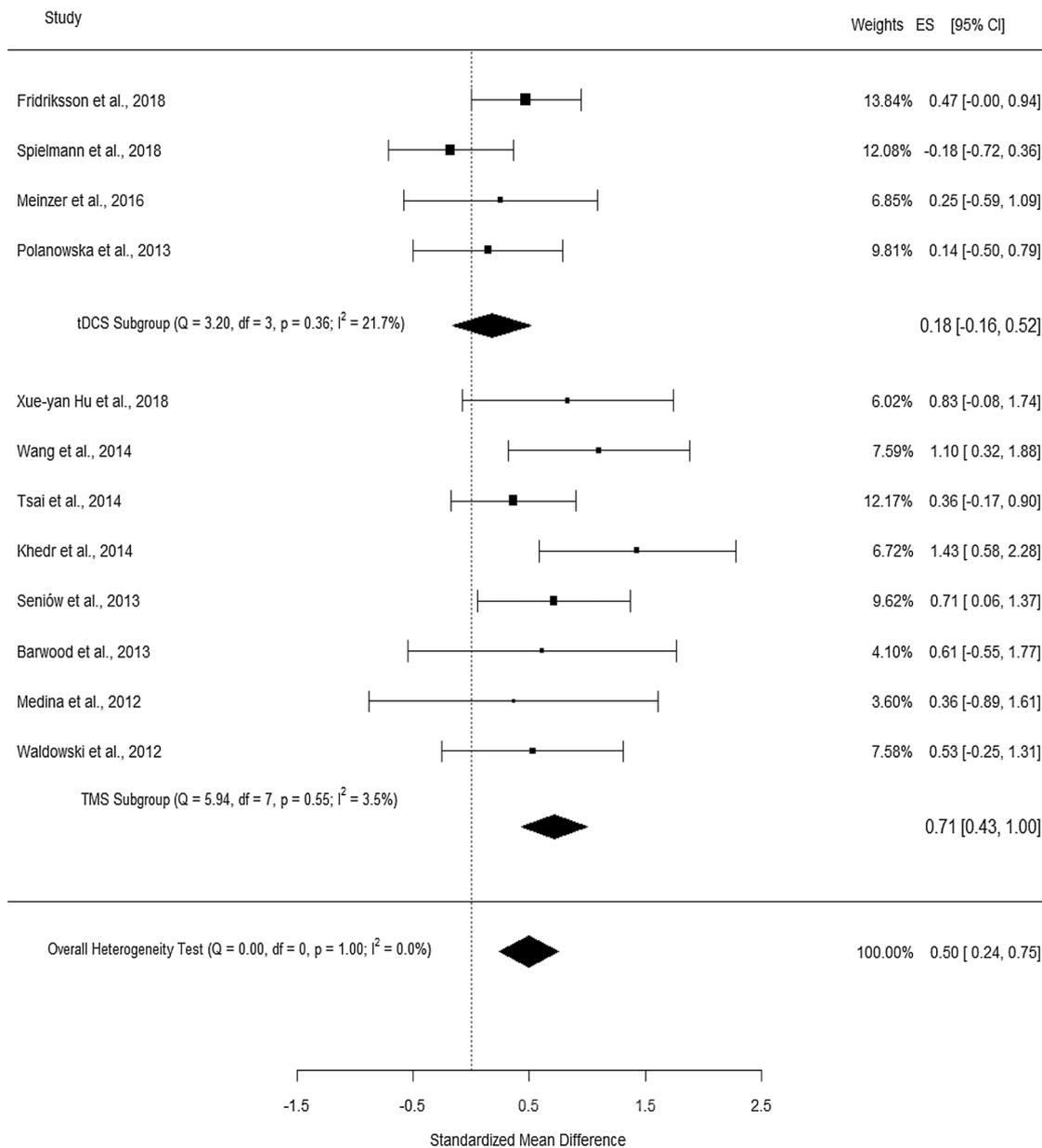


Fig. 3. Forest plot of RCTs at follow-up, broken down by NIBS (TMS vs. tDCS).

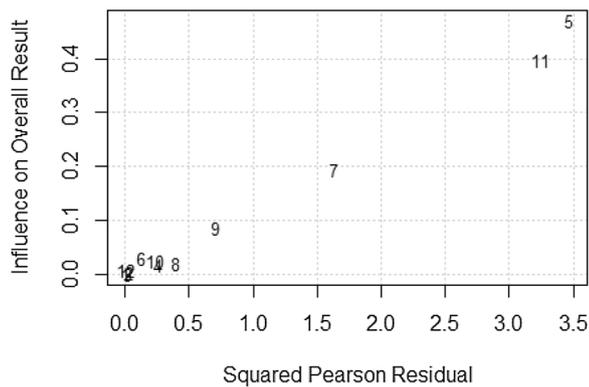


Fig. 3.1.0. Baujat plot at follow-up only RCTs (TMS & tDCS).

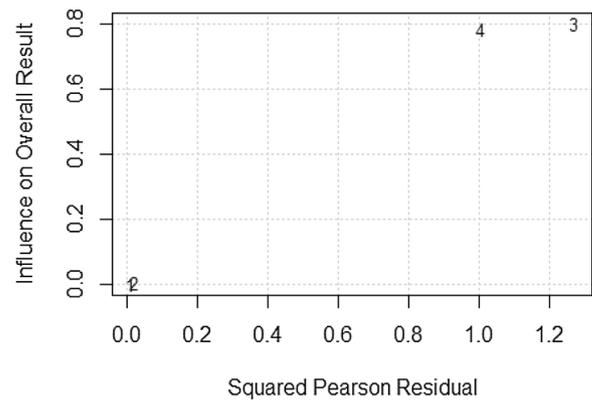


Fig. 3.1.2. Baujat plot of tDCS RCTs at follow-up.

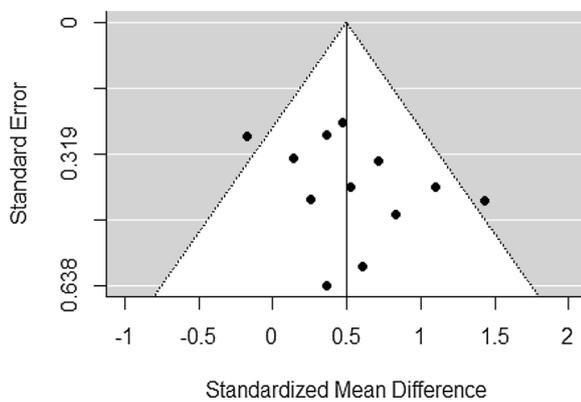


Fig. 3.2.0. Trim and fill funnel plot at follow-up (overall RCTs).

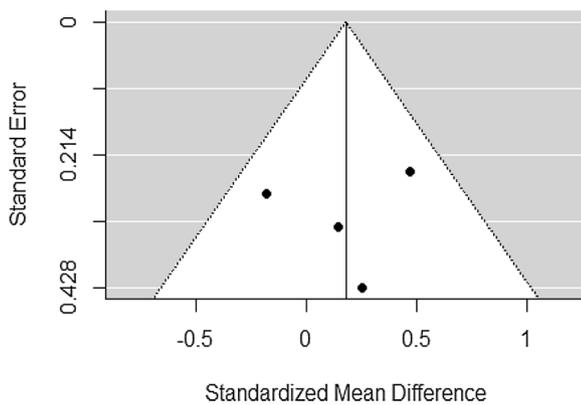


Fig. 3.2.2. Trim and Fill Funnel plot of tDCS RCTs at follow-up.

(that chose the best response area (Fridriksson et al., 2018; Shah-Basak et al., 2015)) the anode was placed over the left, anterior language areas and the cathode over the right supraorbital region.

### 3.3.3. The intensity and duration

of the stimulation were heterogeneous across studies, tDCS being delivered at an intensity of 1 mA or 2 mA (7 out of 8 publications used 1 mA, current density = 0.028) for 10/20 min. Another relevant variation concerned the number of sessions, that ranged between 5 (Fiori et al., 2013; Marangolo et al., 2013a) and 16 (Meinzer et al., 2016). The follow-up period was very broad, varying from one/ two weeks up to 12 months, and some studies had many follow-up time points (e.g. Barwood et al. (2013) evaluated the rTMS effects at 1 week, 2 months, 8 months and 12 months after stimulation), but in this meta-analysis only a period between one and six months was taken into consideration.

### 3.3.4. Associated therapies

In two rTMS studies (Barwood et al., 2013; Medina et al., 2012) the treatment was limited to neurostimulation; in all other cases rTMS and tDCS were delivered together (during the stimulation or immediately after) with a broad range of aphasia classic therapies like: speech and language training for 30–60 minutes two-five times a week, picture-naming activity during every stimulation session, conversational therapy, word-finding therapy and computerized anomia treatment (Tables 3 and 4).

### 3.3.5. Placebo

All the RCTs and randomized crossover studies, apart from Marangolo et al. (2013a) and Hu et al. (2018) were double-blind sham-controlled, i.e., investigators and patients were blinded to the treatment allocations. Randomization was used to assign patients to the treatment or control group but the method of randomization was not always

reported (Table 7a and 7b). In the rTMS experiments, sham stimulation was obtained by positioning the angle of the coil at 90° perpendicular to the skull (Seniów et al., 2013; Khedr et al., 2014; Medina et al., 2012) or with a sham coil (Waldowski et al., 2012; Barwood et al., 2013; Tsai et al., 2014; Wang et al., 2014). In the tDCS experiments, the sham condition implied turning off the stimulation after a very brief period, 15–60 seconds.

### 3.3.6. Outcome measures

Outcome assessment varied largely across studies and included: picture naming, naming reaction times, comprehension, fluency (discourse productivity), grammatical accuracy, lexical selection, general language scores on aphasia batteries (e.g., Western Aphasia Battery - Aphasia Quotient), single photon emission-computed tomography (SPECT) scans, relation between cerebral blood flow (CBF) and language recovery etc.

### 3.3.7. Adverse effects

Overall, both rTMS and tDCS were well tolerated and only common, mild side effects, such as local discomfort at the stimulation site (itching, tingling) or dull headache and dizziness (Fridriksson et al., 2018), were registered. Importantly no study reported significant differences between the active and the control group regarding unpleasant effects, but unfortunately almost half of the included papers did not provide such information (Fiori et al., 2013; Marangolo et al., 2013a; Marangolo et al., 2013b).

## 3.4. Meta-analysis results

Hedges' *g*, a measure of effect size, was computed for each study and pooled into the meta-analysis in an effort to obtain a better understanding of how well the post-stroke aphasia NIBS treatment worked (the primary outcome was based on picture naming accuracy). Hedges' *g* interpretation is very similar to Cohens' *d* (a *g* of 1 indicates that the two groups differ by one standard deviation, a *g* of 2 indicates they differ by two standard deviations). Cohen suggested a rule of thumb for interpreting the results: small effect = 0.2, medium effect = 0.5 and large effect = 0.8 (DeVellis, 1991).

In order to calculate the treatment effect, the standardized mean differences (SMD) were pooled using the **random-effects model** regardless of the heterogeneity test results (*Q* or *I*<sup>2</sup>), since there is a certain amount of variance between studies due to their particular characteristics (e.g., stimulation parameters, associated therapies, patients' characteristics). Table 8 contains the test results from all the analyses.

### 3.4.1. rTMS vs. tDCS follow-up efficacy

rTMS vs. tDCS follow-up efficacy was the main question of the present study; the meta-analysis of 11 RCTs and 5 crossover studies showed a significant medium effect of noninvasive brain stimulation for post-stroke aphasia rehabilitation (overall SMD of 0.53; 95% CI = [0.30, 0.75], *p* < .0001; *I*<sup>2</sup> = 24.78%), see Fig. 2. When separately investigating the effects of rTMS and tDCS, though, both techniques produced a statistically significant effect: an rTMS pooled analysis revealed a moderate effect size (rTMS: SMD = 0.71; 95% CI = [0.43, 1.00], *p* < 0.0001; *I*<sup>2</sup> = 3.54%; *N* = 8), while tDCS produced a significant but small effect size (tDCS: SMD = 0.33; 95% CI = [0.03, 0.62], *p* = 0.02; *I*<sup>2</sup> = 18.32%; *N* = 8); nevertheless the Test of Moderators, comparing the two techniques did not reveal a statistical significant difference between the two (QM(1) = 3.376, *p* = 0.066). Since these data are mainly based on naming scores (2 studies used *speech* as the main outcome (Marangolo et al., 2013b; Medina et al., 2012) and 1 study (Shah-Basak et al., 2015) used the *WAB-QB scores*) the effect of NIBS on language will be more appropriately referred to as the effect on naming.

Although *Q*-statistic and *I*<sup>2</sup> tests provide evidence for heterogeneity,

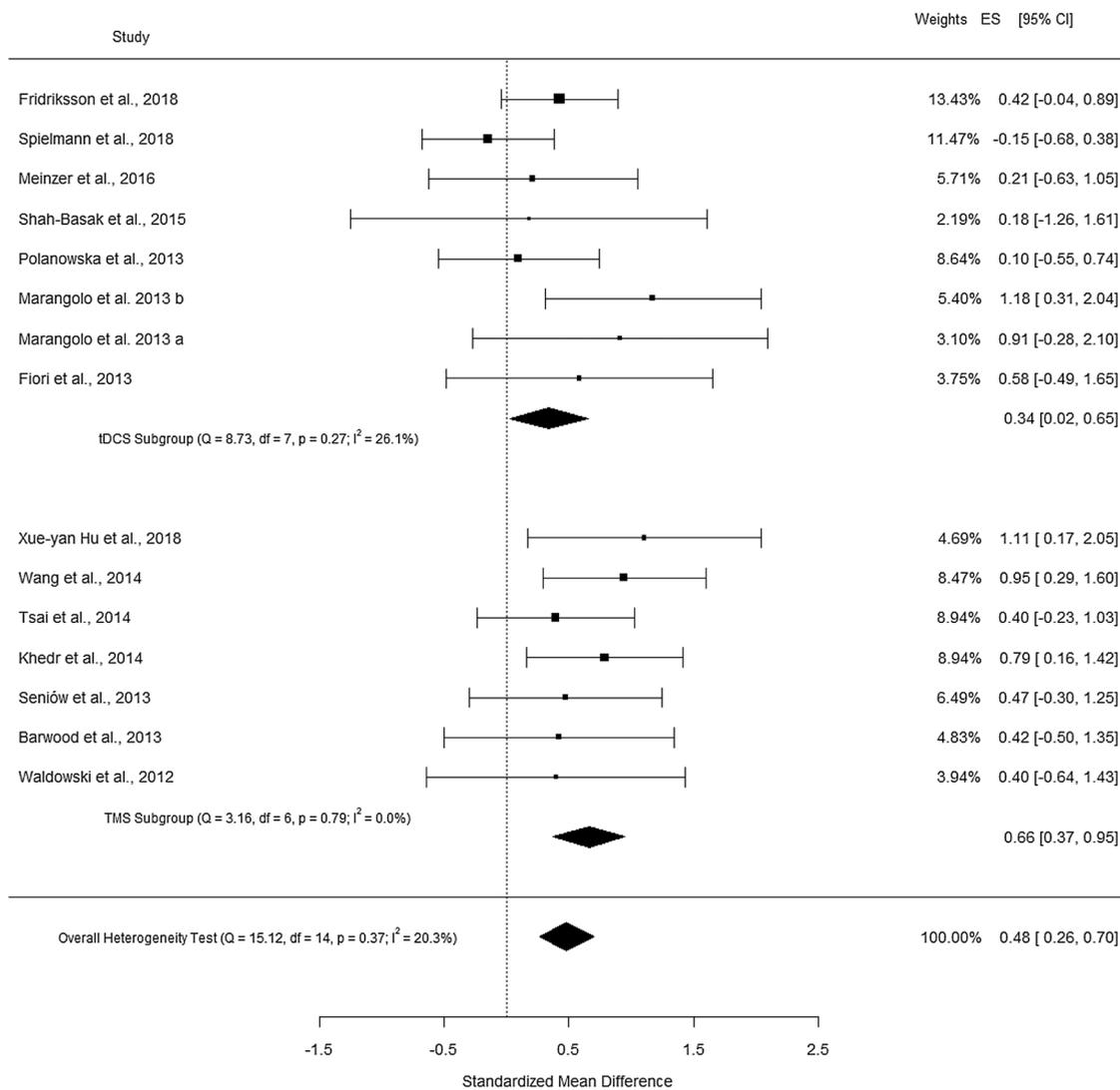


Fig. 4. Forest plot of effect sizes immediately after treatment, broken down by NIBS (TMS vs. tDCS).

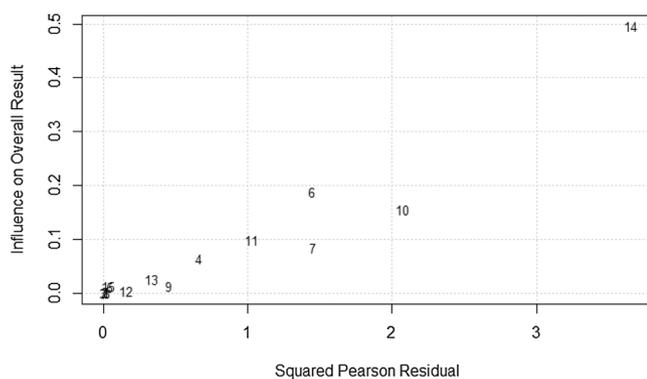


Fig. 4.1.0. Baujat plot immediately after treatment (TMS & tDCS).

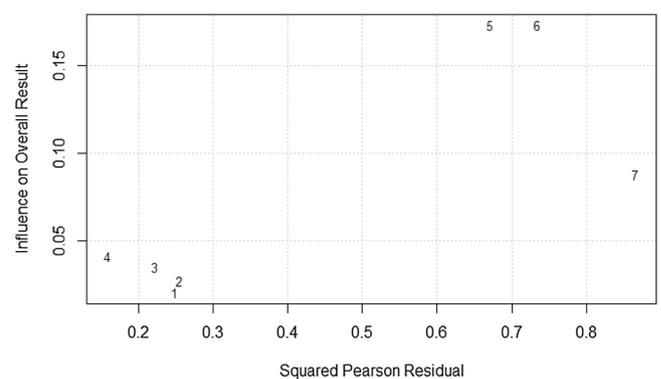


Fig. 4.1.1. Baujat plot of TMS studies immediately after treatment.

they do not offer an indication about which studies may disproportionately influence heterogeneity. Baujat et al. (2002) proposed a plot to reveal those papers which contribute more heavily to heterogeneity and overall outcome (Fig. 2.1.0 Figure 2.1). Studies in the top right quadrant of Fig. 2.1.2 for tDCS (Spielmann et al., 2018) and Fig. 2.1.1 for rTMS (Tsai et al., 2014) were those with the higher contribution to overall heterogeneity and final results. Nevertheless, the visual inspection of a plot might not be conclusive; therefore, to identify

potential outliers and influential studies, Viechtbauer and Cheung (Viechtbauer and MW-L, 2010) proposed an influential test derived from standard linear regression. Results indicated that Tsai et al. (2014) (study 6 on the Baujat plot), for the rTMS subgroup, and Spielmann et al. (2018) (study 7 on the Baujat plot), for the tDCS subgroup, yield observed effects that were well separated from the rest of the data. Looking at the forest plot it can be easily seen that Shah-Basak et al.'s (2015) paper crucially contributes to the final result (weights =

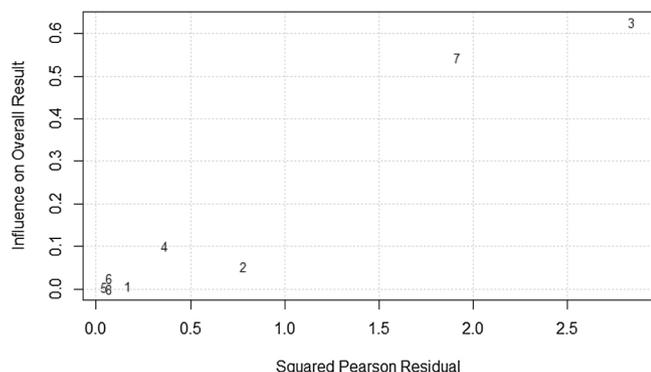


Fig. 4.1.2. Baujat plot of tDCS studies immediately after treatment.

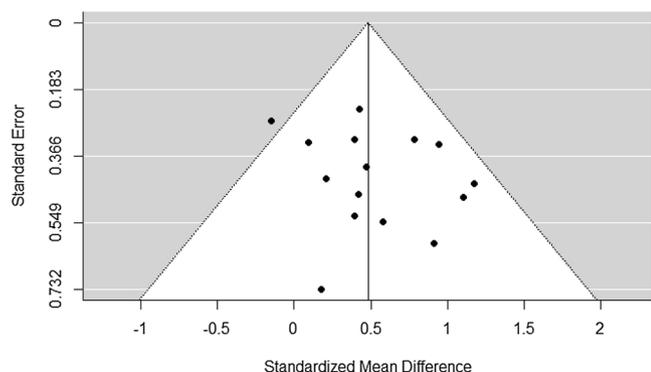


Fig. 4.2.0. Funnel plot immediately after treatment (TMS & tDCS).

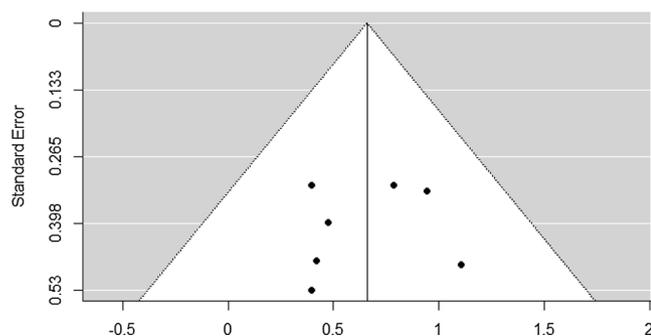


Fig. 4.2.1. Trim and fill funnel plot immediately after treatment (TMS only).

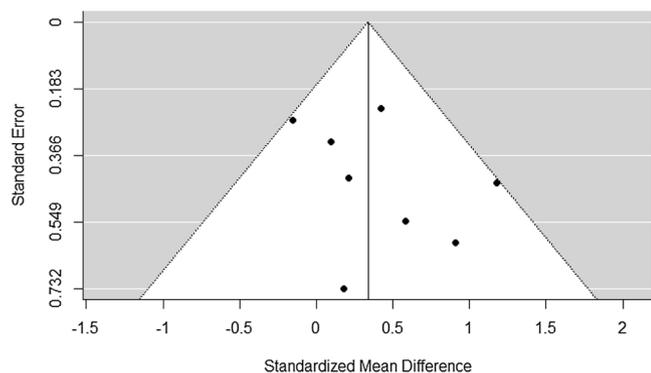


Fig. 4.2.2. Trim and Fill Funnel plot of tDCS After.

10.61%) and Spielmann et al.’s (2018) study can be considered an outlier since the reported effect size is negative (−0.18), contrary to all the other studies: indeed, in this study tDCS on subacute patients seems to have a slightly (not statistically significant) negative effect on

language recovery.

**Publication Bias:** The funnel plot for rTMS, tDCS and the overall publication bias (Fig. 2.2.0, 2.2.1 and 2.2.2) was considered symmetrical given the fact that neither the Rank Correlation nor Egger’s Regression Test were statistically significant (Table 8); so, the conclusions regarding the rTMS and tDCS follow-up efficacy, taken alone and pooled together, remained unchanged.

3.4.2. Only tDCS RCTs

Only tDCS RCTs were then analyzed separately (N = 4) in order to exclude possible confounding factors like the carry over effects, which were present in the majority of the crossover trials (Fiori et al., 2013; Marangolo et al., 2013a; Marangolo et al., 2013b; Shah-Basak et al., 2015). The “only RCTs analysis” was not conducted on the TMS studies because, the only TMS randomized crossover trial was the one by Medina et al. (2012) who provide the follow-up results for treatment and control before the sham participants crossed over into the real treatment group, which means that we extract the same data as from an RCT study.

The overall weighted mean effect size for rTMS and tDCS was 0.49 (p = .0001; 95% CI: [0.24, 0.75]; N = 12). The test for heterogeneity was not significant (Q = 15.57, p = .16, I<sup>2</sup> = 33.14%), indicating that the variance between studies was not larger than expected when including random sample error (Fig. 3). Taken separately the tDCS RCTs effect size was small and non-significant SMD = 0.20 (p = 0.29; 95% CI: [-0.15 - 0.51]; N = 4), and as expected the Test of Moderators showed that the difference between the TMS RCTs and tDCS RCTs estimates was statistical significant (QM (1) = 5.61, p = 0.018).

The Baujat plot (Fig. 3.1.0, 3.1.2) and the Viechtbauer and Cheung (Viechtbauer and MW-L, 2010) influential test identified two studies as potential outliers: Spielmann et al. (2018) and Fridriksson et al. (2018) (study 3 and study 4) for the tDCS subgroup. The publication bias tests were not significant and the funnel plots (Fig. 3.2.0, 3.2.2) can be considered symmetrical.

3.4.3. After vs. Follow-up

Our meta-analysis focus was the NIBS follow-up efficacy but we also collected and analyzed the SMD immediately after treatment in order to explore the effect of time on brain stimulation efficacy (once again, the primary outcome was based on naming scores). Separate analysis of tDCS and rTMS publications immediately after treatment (no more than one week later) revealed a statistically significant but small SMD of 0.34 (95% CI = [0.023, 0.65]; p = 0.035; N = 8) for tDCS, while for rTMS studies, the SMD of 0.66 (95% CI = [0.37, 0.94]; p < .0001; N = 7) can be considered medium (Fig. 4). Furthermore, the paired t-test comparing before vs after effect sizes for each technique yielded no significant difference between the two time points, indicating that the effect size observed in the rTMS (t (6) = −0.54, p = 0.24; 99%CI = [−0.54, 0.24]) and tDCS (t (7) = 0.14, p = 0.88; 99%CI = [−0.16, 0.17]) studies immediately after treatment did not change significantly when measured at follow-up (an interval extending from one to six months after the last stimulation session).

The Viechtbauer and Cheung (Viechtbauer and MW-L, 2010) influential test as the Baujat plot (Fig. 4.1.0, 4.1.1, 4.1.2) showed no potential outliers for the rTMS alone, while the Spielmann et al.’s (2018) and Marangolo et al.’s (2013b) experiments were identified as potential outliers for tDCS effects. The tests for publication bias indicated no need for bias correction (Fig. 4.2.0, 4.2.1, 4.2.2).

3.4.4. Chronic vs. Subacute

The stroke phase (subacute or chronic) determines the brain state and ongoing plastic changes which influence treatment effects. To investigate possible differences in NIBS efficacy at follow-up taking into consideration the time passed from the stroke event, studies including only chronic patients (N = 11, tDCS = 6 and rTMS = 5) were analyzed separately from those with subacute aphasic participants (N = 5,

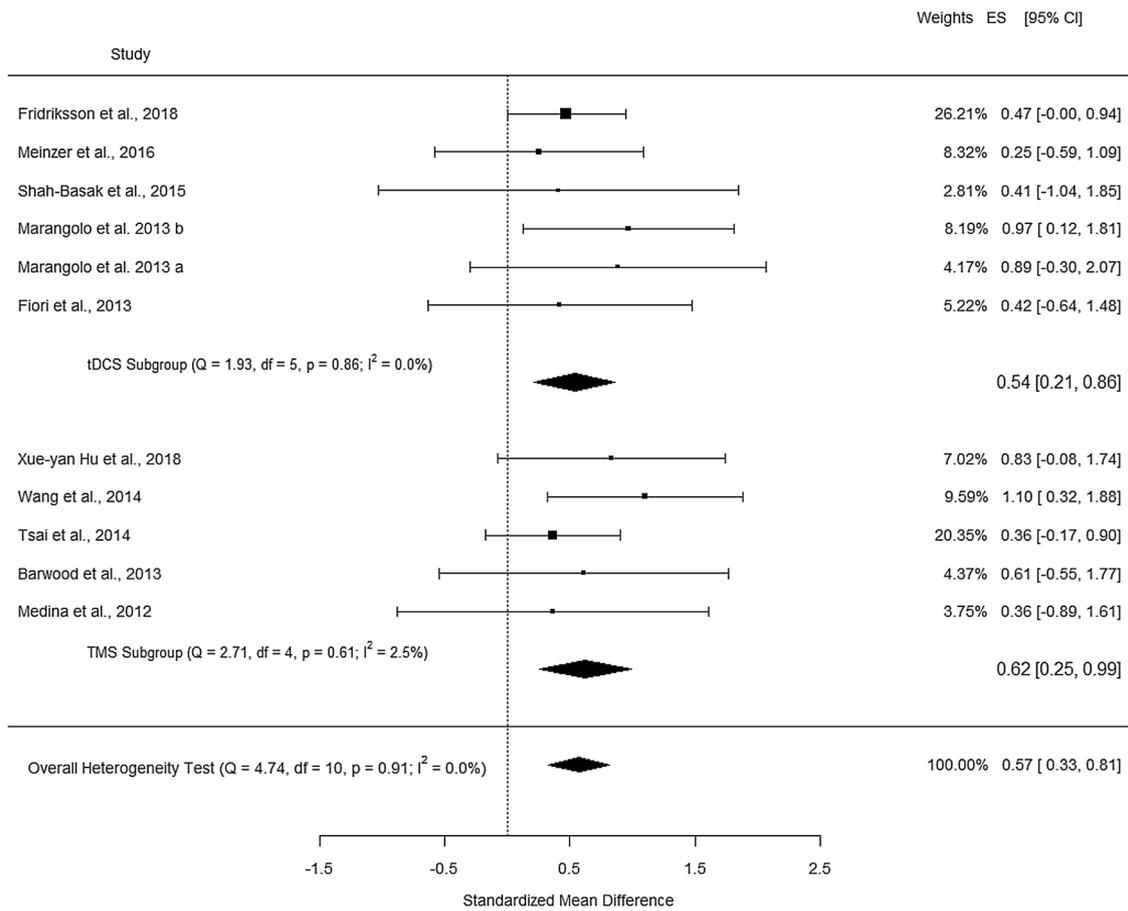


Fig. 5. Forest plot of chronic subgroup effect sizes at follow-up, broken down by NIBS (TMS vs. tDCS).

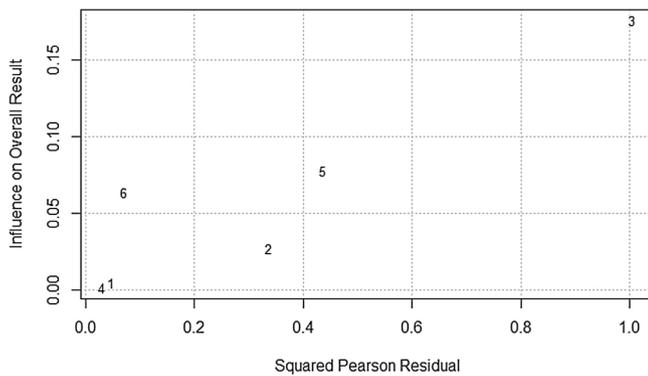


Fig. 5.1.0. Baujat plot of chronic subgroup at follow-up (TMS & tDCS).

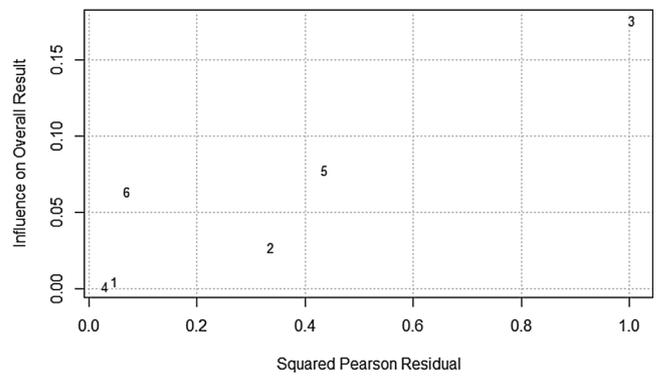


Fig. 5.1.2. Baujat plot of chronic subgroup at follow-up (tDCS only).

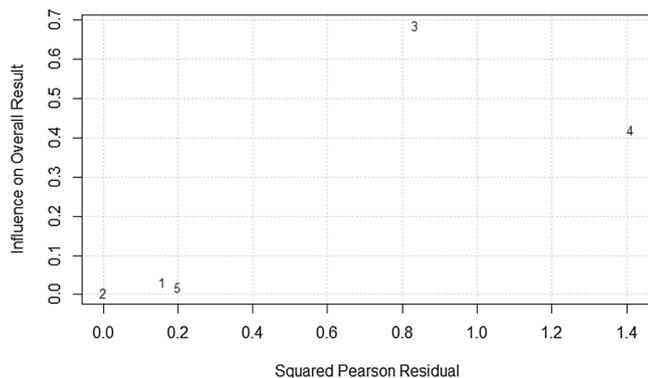


Fig. 5.1.1. Baujat plot of chronic subgroup at follow-up (TMS only).

rTMS = 3, tDCS = 2) and the two techniques were compared for each subgroup. This choice was made based on the previous analysis (rTMS vs. tDCS at follow-up) showing that rTMS and tDCS produced different results especially concerning the subacute population.

**rTMS vs. tDCS in chronic aphasia (more than six months after the stroke):** The outcome revealed a significant weighted mean effect sizes of 0.62 (95% CI: [0.25, 0.98], p = 0.001, N = 5) for the rTMS studies and 0.54 (95% CI: [0.20, 0.86], p = 0.001, N = 6) for the tDCS studies, while the Test of Moderators (QM (1) = 0.20, p = 0.65) showed no significant difference between the two effect sizes (for details see Fig. 5, and funnel plots Figs. 5.2.0, 5.2.1, 5.2.2).

Taking a close look to the influential studies, the test revealed three potential outliers: Wang et al. (2014) and Tsai et al. (2014) for the rTMS subgroup, and Fridriksson et al. (2018) for the tDCS subgroup (Baujat plot Fig. 5.1.0, 5.1.1, 5.1.2).

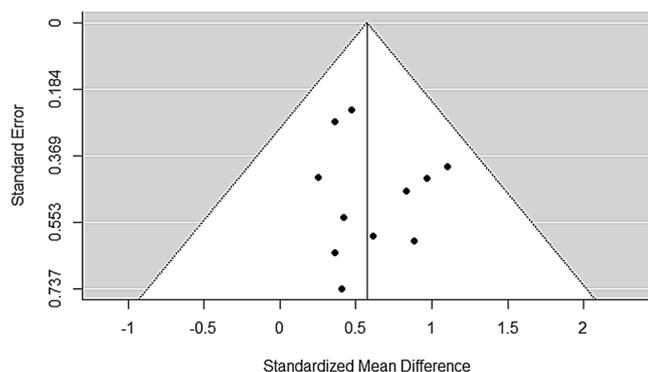


Fig. 5.2.0. Publication bias assessed by funnel plot of chronic subgroup (TMS & tDCS).

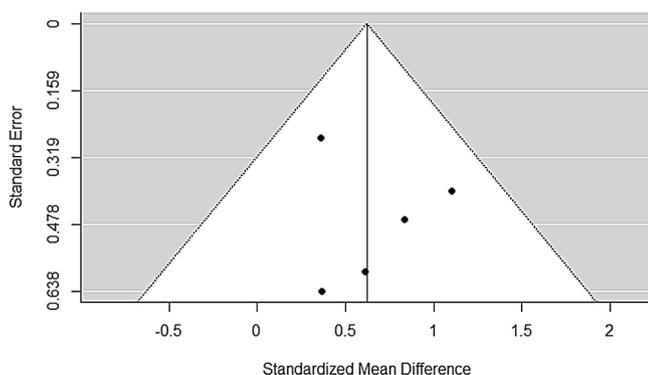


Fig. 5.2.1. Funnel plot of chronic subgroup at follow-up (TMS only).

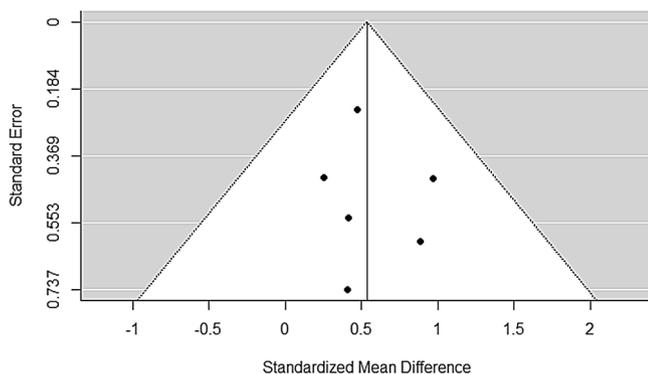


Fig. 5.2.2. Funnel plot of chronic subgroup at follow-up (tDCS only).

**rTMS vs. tDCS in subacute aphasia (less than six months after stroke):** The number of studies investigating the effects of NIBS exclusively on a subacute population was particularly small (rTMS = 3 and tDCS = 2). The pooled analysis revealed a statistically large and significant SMD of 0.85 (95% CI = [0.30, 1.32];  $p = 0.0004$ ) for rTMS studies in subacute patients, while for tDCS the SMD was not calculated because, with such a small number of studies, the result is neither solid nor reliable. (Fig. 6, 6.1.0, 6.1.1, 6.2.0, 6.2.1).

### 3.5. GRADE assessment

Overall evidence was qualified using GRADE (for RCTs and crossover). Low quality of evidence (i.e., the true effect might be markedly different from the estimated effect) shows that people with post-stroke aphasia may have a small to medium long-term benefit from tDCS treatment when compared to the control group; while a high quality of evidence (i.e., the authors believe that the true effect is probably close

to the estimated effect) indicates that aphasic patients might have a medium to large benefit from rTMS treatment.

Given the fact that the online GRADEpro software offers only two options for the study designs, namely RCTs or observational studies, we chose RCTs, because the majority of the included studies were randomized designs. The level of evidence for RCTs was downgraded due to the carry over effect in the crossover designs but also for the lack of precision due to incongruent effect size direction and the large confidence intervals. The GRADE data are shown in Table 9.

## 4. Discussion

In recent years, an increasing number of studies investigated whether tDCS or TMS can promote aphasia recovery, in an attempt to potentiate the therapy-induced clinical benefits and/or to shorten the period of treatment.

As mentioned in the introduction, the aim of this comparative meta-analysis was to examine the long-term efficacy and reliability of NIBS (tDCS, rTMS) as an intervention for post-stroke aphasia. In other words, we aimed at assessing to what extent the therapeutic promises are confirmed in the long term, so that rTMS and/or tDCS (either as an add-on therapy to SLT or as monotherapy) can be considered really effective.

The overall analysis, including 16 independent follow-up effect sizes (mainly based on naming scores), revealed a medium and significant effect of NIBS (rTMS and tDCS studies pooled together) compared to the control condition (sham or pre-treatment). These data are highly relevant for the rehabilitation research field, suggesting that rTMS and tDCS may improve aphasia recovery and produce durable results, especially for the naming performance. The effect size hereby found is comparable to those reported by other recent meta-analyses investigating the same topic, despite the fact that their analyses were based on data recorded immediately after the end of treatment (Shah-Basak et al., 2016; Otal et al., 2015). Although the magnitude of the treatment effect size was larger in the rTMS than in the tDCS studies, this difference was not statistically significant. Nevertheless, when balancing these results by the GRADE level of evidence it seems that: i) while rTMS coupled with SLT can be considered effective (a medium effect size at follow up and a high level of evidence), ii) there are no consistent data to make a strong recommendation regarding the effectiveness of tDCS coupled with SLT in improving post-stroke aphasia (a small to medium effect size at follow up and a low level of evidence, as qualified with GRADE). This means that in some conditions (e.g., anodal stimulation in the subacute population), tDCS therapy could be less effective (Spielmann et al., 2018).

Critically, comparing the data immediately after treatment and at follow-up, we found no significant differences between the two time-points. Therefore, we can provide compelling evidence that the treatment effects are maintained in time, i.e., the changes observed at the end of the stimulation intervention remained roughly stable (they insignificantly decrease or do not improve) when measured again after a period extending from one to six months post-treatment.

Considering only RCT studies, in order to exclude eventual confounding variables, such as carry-over effects, we observed that the overall (rTMS and tDCS) effect size remained medium and statistically significant, but sub-analyses indicated an advantage of rTMS over tDCS. More precisely the tDCS RCTs effect size was small and not statistically significant. This result should be interpreted with caution since the number of studies is extremely small. From the four tDCS RCTs, two were conducted on subacute aphasics (Polanowska et al., 2013; Spielmann et al., 2018) and as previously observed, the tDCS effect seems to be sensitive to chronicity. Furthermore, none of the tDCS RCTs, on chronic populations, stimulated the perilesional Broca's area; specifically, Meinzer et al. (2016) applied anodal tDCS over the left primary motor cortex, while Fridriksson et al. (2018) choose to stimulate the left temporal lobe, specifically, the region with the highest

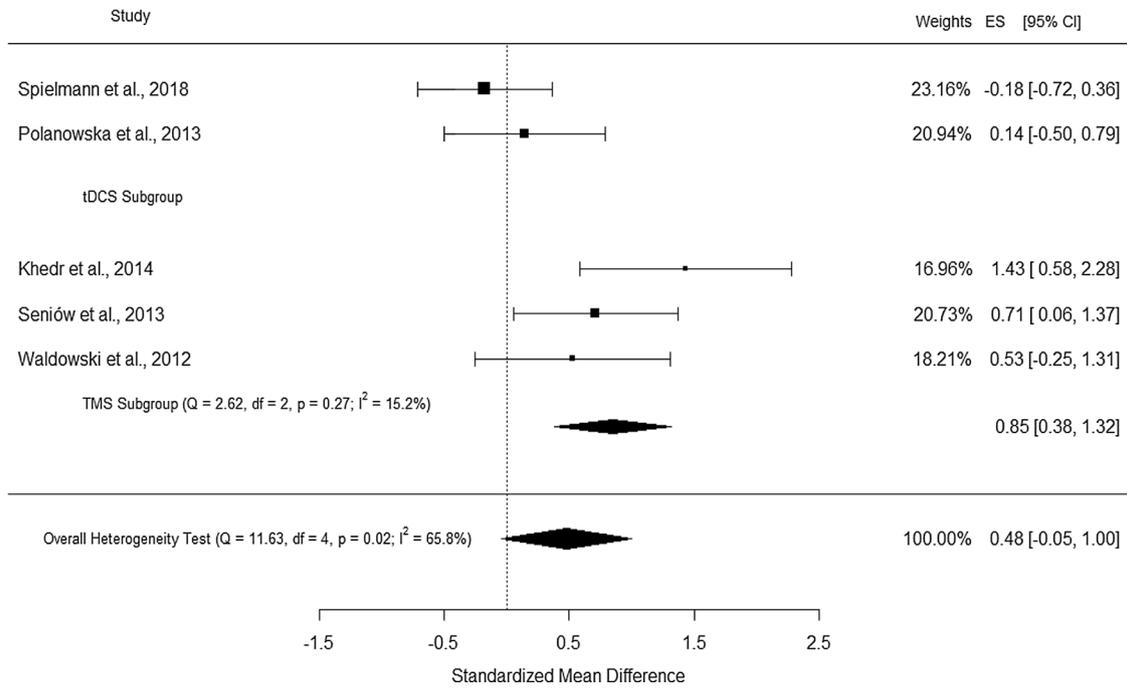


Fig. 6. Forest plot of subacute subgroup effect sizes at follow-up, TMS and tDCS.

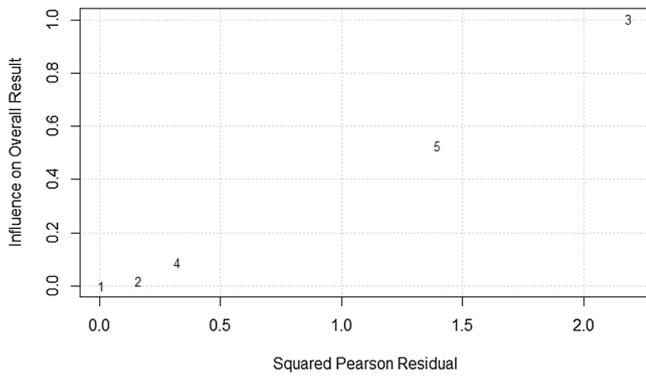


Fig. 6.1.0. Baujat plot of subacute subgroup at follow-up (TMS & tDCS).

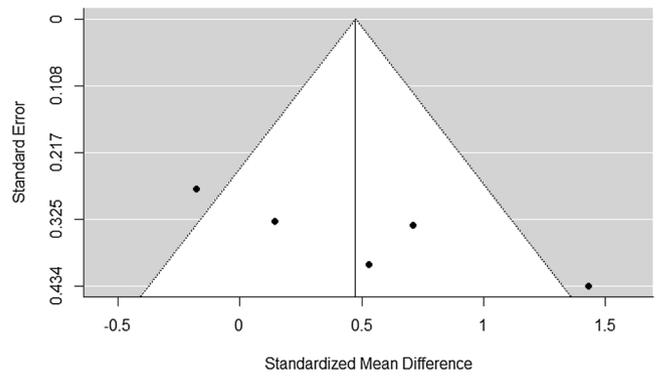


Fig. 6.2.0. Trim and fill funnel plot of subacute subgroup (TMS & tDCS).

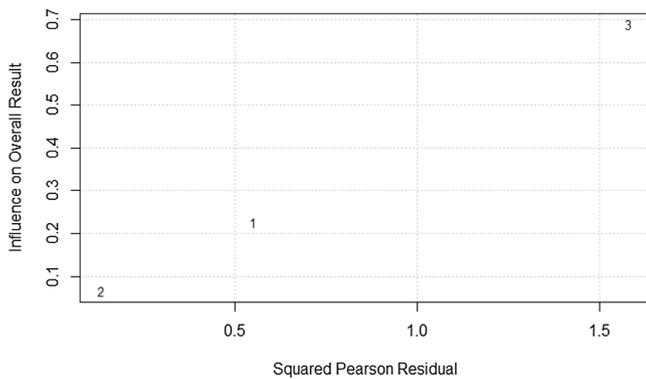


Fig. 6.1.1. Baujat plot of subacute subgroup at follow-up (TMS only).

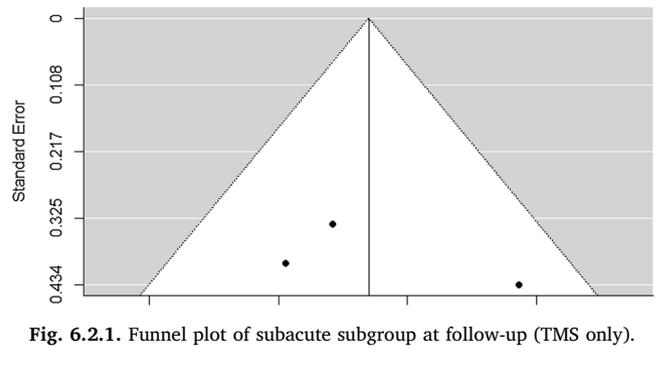


Fig. 6.2.1. Funnel plot of subacute subgroup at follow-up (TMS only).

naming related activation during fMRI.

The sub-analysis by stroke chronicity confirmed the previous observations (based on data recorded immediately after treatment) (Shah-Basak et al., 2016), namely, that also at follow-up rTMS was effective in both chronic and subacute aphasic patients while tDCS was effective only in the chronic phase. Only two studies investigated the tDCS efficacy during the subacute phase (Polanowska et al., 2013; Spielmann

et al., 2018) and both failed to find significant differences in language outcomes between groups (treatment vs sham). Based on the current literature data, it is unclear whether the difficulty to find an improvement (after tDCS stimulation in the subacute aphasic population) is because there is no effect at all or a “true effect” is too small to be detected with such a small number of studies. It has been speculated that an effect of tDCS might be difficult to achieve during the subacute phase, due to spontaneous recovery, that could mask the effects of rehabilitation interventions (Polanowska et al., 2013; Spielmann et al.,

**Table 9**  
GRADEpro summary.

Question: Long-term efficacy of transcranial brain stimulation (TMS & tDCS) vs. Control in post-stroke aphasia treatment.									
Certainty assessment						№ of patients	Effect	Certainty	
№ of studies	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	Transcranial brain stimulation	Control	Absolute (95% CI)	
8	Long-term efficacy of tDCS vs. Control (follow up: range 4 weeks to 24 weeks; Scale from: -1.5 to 2.5) randomized trials	serious <sup>a</sup>	serious <sup>b</sup>	not serious	not serious	119	132	SMD 0.33 SD higher (0.03 higher to 0.6 higher)	⊕⊕○○ LOW
4	Long-term efficacy of tDCS vs. Sham (RCT only) (follow up: range 4 weeks to 12 weeks; Scale from: -1.5 to 2.5) randomized trials	not serious	serious <sup>b</sup>	not serious	serious <sup>c</sup>	88	103	SMD 0.18 SD higher (0.15 lower to 0.51 higher)	⊕⊕○○ LOW
8	Long-term efficacy of TMS vs. Sham (RCT only) (follow up: range 8 weeks to 15 weeks; Scale from: -1.5 to 2.5) randomized trials	not serious	not serious	not serious	not serious	118	99	SMD 0.71 SD higher (0.43 higher to 0.996 higher)	⊕⊕⊕⊕ HIGH
11	Long-term efficacy of NIBS vs. Control in patients with chronic aphasia. (follow up: range 4 weeks to 24 weeks; Scale from: -1.5 to 2.5) randomized trials	serious <sup>a</sup>	not serious	not serious	not serious	145	139	SMD 0.57 SD higher (0.33 higher to 0.81 higher)	⊕⊕⊕○ MODERATE
5	Long-term efficacy of NIBS vs. Control in patients with subacute aphasia. (follow up: range 4 weeks to 15 weeks; Scale from: -1.5 to 2.5) randomized trials	not serious	serious <sup>b</sup>	not serious	serious <sup>c</sup>	92	92	SMD 0.48 SD higher (0.05 lower to 1.00 higher)	⊕⊕○○ LOW

CI: Confidence interval; SMD: Standardized mean difference (Hedges'g).

GRADE Working Group grades of evidence.

**High quality:** Further research is very unlikely to change our confidence in the estimate of effect.

**Moderate quality:** The authors believe that the true effect is probably close to the estimated effect.

**Low quality:** Further research is very likely to have an important impact on our confidence in the estimated effect and could change the estimate.

**Very low quality:** We are very uncertain about the estimate.

Downgraded Explanations.

<sup>a</sup> Downgraded as there were serious limitations identified in the risk of bias, since not all the studies were RCTs, some were crossover or open-label studies.

<sup>b</sup> Point estimates vary widely and the direction of the effect was not consistent.

<sup>c</sup> A very small number of included studies.

2018). Another explanation might be the relation between the stimulation parameters (inhibitory vs. excitatory, ipsilateral vs. contralateral) and the dynamic mechanisms of post-stroke recovery (repair of damaged networks, activation of compensatory areas in the right hemisphere, or activation of previously functionally inactive pathways) and how well each one supports the other in order to enhance recovery. For example, Polanowska et al. (2013) and Spielmann et al. (2018) using anodal stimulation over the left Broca's area obtained a null effect, while You et al. (2011) showed that auditory verbal comprehension improved significantly in subacute patients treated with cathodal tDCS over the right superior temporal gyrus, as compared to patients in the other groups (anodal tDCS applied to the left superior temporal gyrus and sham). In 2006, Saur (2006) reported that brain reorganization during language recovery might proceed in phases. Namely, they observed a reduced activation of the spared left language areas during the acute period, followed by the recruitment of the right language regions in the subacute phase, and a re-shift of peak activation to left-hemispheric language areas (which was associated with further language improvement) (Saur and Hartwigsen, 2012). Considering this observation, and knowing that tDCS has a modulation effect (it only modulates those neurons that are potentially engaged in the execution of a given task) (Fertonani and Miniussi, 2017), it might be more appropriate to try to downregulate the right hemisphere during the subacute period (cathodal tDCS over the right language areas) and to activate the perilesional regions during the chronic phase (eventually by using a bi-hemispheric stimulation: cathode over the right and anode over the left language areas). However, the choice of the stimulation type (inhibitory or excitatory) and the stimulation area (right or left hemisphere) depends also on the adopted recovery model (the "vicariation model" - right areas help recovery, the "interhemispheric competition model" - the right hemisphere excessively inhibits the left one, and the "bimodal balance-recovery model" - the quantity of spared neuronal structures determines the network reorganization) (Di Pino et al., 2014).

There are however several limitations in the present meta-analysis, as, for instance, the low number of studies (especially because many papers did not include a follow-up period), the risk of bias (present in the crossover designs) and the selection biases. The between-study heterogeneity and the risk of publication bias were low. Nevertheless, even if the funnel plot and the specific asymmetry tests did not indicate a significant publication bias, we restricted our search strategy to articles published in English, excluding potentially high-quality research data that were published in other languages or belonging to "gray literature". Crucially, all the comments and recommendations were based on publications reporting follow-up results; this means that other relevant information about efficacy, stimulation protocol and methodology might have been missed (for reviews see (de Aguiar et al., 2015; Sebastianelli et al., 2017; Shah-Basak et al., 2016; Kapoor, 2017; Otal et al., 2015; Ren et al., 2014; Crinion, 2016)). However, we believe that the relevant outcome is a permanent, or at least a long-lasting improvement, not just an immediate one. Another limitation is due to an important literature bias, namely, the lack of comprehensive aphasia assessment in patients receiving NIBS treatment. Since picture naming is one of the most frequently used tests for assessing improvement in language abilities after rTMS or tDCS (Shah-Basak et al., 2016), it was used as the main outcome for this review. We are aware that picture naming accuracy is not the unique measure of aphasia severity and, consequently, the meta-analysis results only reflect the effects of NIBS on naming in persons with aphasia.

Summing up, our findings add new data to the existing literature, by showing that, with the current stimulation procedures, the rTMS long-term effect size is moderate but more reliable independently of the patients' characteristics, while tDCS appears moderately effective for the chronic population. Importantly, study quality was lower in the tDCS subgroup (Table 9, GRADEpro evaluation). Many studies used crossover designs with a very small period between the sessions, therefore the final result (especially at follow-up) was probably a mix between the different experimental conditions. Another important

problem observed in tDCS studies was the lack of details regarding lesion size, and given the dimension of the tDCS electrodes (often  $5 \times 7$  cm), it is not always obvious that all patients actually had a structurally intact cortex underneath the active electrode.

Based on the current data and the literature reviews (e.g. (Bolognini and Miniussi, 2018)), we can speculate that NIBS (tDCS and rTMS) are more effective on boosting the recovery process, not as a monotherapy (a treatment by itself), but rather as a complementary instrument coupled with SLT (only five included studies used rTMS and tDCS alone).

In conclusion, each technique has advantages and disadvantages: rTMS seems more effective but also more expensive and with a higher safety risk, while tDCS appears less effective but is user-friendly and could be applied at home with a relatively small cost. For these reasons, further evaluation of the utility of these methods for aphasia rehabilitation should combine efficacy and feasibility data, making a cost-benefit analysis possible. Still, in the future the most important challenge will be to collect clear evidence of the long-term efficacy in the everyday-life of these methods.

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