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Investigating NIBS for language rehabilitation in aphasia

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ABSTRACT

Purpose: The purpose of this scoping review was to identify and synthesize research on interventions in which noninvasive brain stimulation (NIBS) was used to improve linguistic abilities in individuals with aphasia. NIBS comprising transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) are emerging technologies with potential to improve the underlying neurobiology of language in brains with stroke-induced lesions.
Methods: The results of a systematic search of electronic literature databases were reviewed in CADIMA software by two authors yielding 57 studies published between 2015 and 2022. Selected articles were reviewed for study characteristics, participant characteristics, intervention details, and outcome measures.
Results: NIBS is largely used for non-fluent aphasia during the chronic phase of recovery for improving naming and comprehension using picture naming and auditory comprehension of words, commands, and small paragraphs. Standardized test materials are used to measure treatment efficiency, with neuroimaging gradually emerging as an added measure to assess the neurobiological changes arising as a result of treatment induced linguistic recovery.
Conclusion: The findings from this scoping review describe the design and delivery of NIBS treatment from subacute to chronic stages of recovery in aphasia. Positive results from heterogenous studies show the potential of NIBS in improving linguistic outcomes for people with aphasia. Large scale clinical trials and systematic reviews should further substantiate our findings of NIBS efficiency for specific language skills (e.g., naming accuracy, sentence production, discourse comprehension).

KEYWORDS
aphasia; neurorehabilitation; noninvasive brain stimulation (NIBS); transcranial direct current stimulation (tDCS); transcranial magnetic stimulation (TMS)

Introduction

Aphasia is an acquired language disorder caused by neurological damage following a stroke. The language difficulties of aphasia limit the individual's participation in socio-professional domains increasing the probability of emotional distress and depression leading to a persistent need to improve the linguistic abilities and quality of life of people with aphasia (Ross & Wertz, 2003, Spaccavento et al., 2014). Speech-language therapy is the primary solution to aid language recovery in aphasia. Additional technological

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applications can further boost speech-language therapy protocols to achieve closer to premorbid levels of functioning during post-stroke recovery (Brady et al., 2016). In recent years, novel technological interventions are being increasingly researched and used adjuvant to speech-language therapy for enhancing communicative outcomes in aphasia (Simmons-Mackie et al., 2013). The current scoping review aims to explore the area of non-invasive brain stimulation (NIBS) for improving linguistic outcomes in aphasia. Scoping reviews can examine the extent of research activity while identifying gaps in research literature and can summarize research findings to determine the future prospect of a systematic review (Arksey & O'Malley, 2005). A scoping review design was used here to identify and summarize clinical parameters of NIBS approaches that support neuroplasticity in the post-stroke brain.

Technology for rehabilitation

Neurorehabilitation is based on an understanding of healthy brain function and post-stroke dysfunction (Kiran & Thompson, 2019). Language recovery in stroke-induced aphasia is based on post-stroke neural reorganization aided through therapeutic treatment that may be enhanced through NIBS. Neural reorganization in post-stroke aphasia constitutes changes in the underlying neural areas representing language functions (Hamilton, et al., 2011). Three models of neuroplasticity that form the basis of neurorehabilitation in aphasia recovery are: (1) inclusion of residual perilesional language areas in the left hemisphere, (2) compensatory inclusion of homotopic language areas in the right hemisphere, and (3) or both recruitment of perilesional left hemisphere language areas and homotopic right hemisphere language areas. In addition, there is sometimes inefficient recruitment of right hemisphere areas that inhibits language recovery in models (2) and (3). The field of neurorehabilitation mainly aims to develop therapeutic solutions for language recovery that stimulate appropriate neural systems through one of the models of neuroplasticity (Szaflarski et al., 2011).

Non-invasive brain stimulation (NIBS) is one route for promoting post-stroke neuroplasticity. It is comprised of transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS). TMS refers to the application of magnetic pulses to a specific position on the scalp (Rossi et al., 2009). TMS works on the principle of electromagnetic induction consisting of a stimulator device, which has capacitors that can hold large currents connected to a coil of copper wires. The stimulator is used to generate a time-varying magnetic field that penetrates the skull and induces an electric current in the neuronal cells perpendicular to the coil. The induced electric current can depolarize the neuronal membrane and modulate the action potentials of nearby neurons. TMS can be delivered in a single pulse or as a set of repetitive pulses per second (rTMS). When rTMS is delivered at a low frequency (<5Hz), it decreases cortical excitability and when delivered at high frequency (>5Hz), it increases cortical excitability (Fitzgerald et al., 2006). Theta burst stimulation (TBS) is a newer protocol that modifies the standard rTMS by producing longer lasting and stable changes in cortical excitability (Huang et al., 2005). TBS consists of three pulses at 50Hz delivered rapidly every 200ms. These pulses can be continuous (cTBS) or interrupted (iTBS) every few seconds. TMS and its variations have been used to support neurorehabilitation by following any one of the models of neuroplasticity, inhibiting and stimulating neural networks in people with mostly chronic aphasia and are evaluated through functional neuroimaging and changes in speech and language therapeutic outcomes (Hamilton et al., 2011).

Another approach in NIBS is transcranial direct current stimulation (tDCS), a neuromodulatory technique that works by passing electric currents of small amplitude (1-2 milliampere, mA) directly through the brain via two large saline-soaked sponge electrodes (often 5X7 cm^2 or 5X5 cm^2, Nitsche & Paulus, 2000). The active electrode that stimulates the brain regions is placed on the target site on the scalp, and the reference electrode that receives the current is placed on the forehead or the unaffected shoulder. The current passing through the electrodes in tDCS is sufficient to modulate the resting membrane potentials of the neuronal cells without generating an action potential. Like rTMS, tDCS can be excitatory and inhibitory. Electrode montage like anodal tDCS (a-tDCS) stimulates cortical excitability, and cathodal tDCS (c-tDCS) inhibits cortical excitability (Nitsche & Paulus, 2000; Nitsche & Paulus, 2001). However, anodal-excitatory, and cathodal-inhibitory dichotomous stimulation often varies based on goal of stimulation e.g., localized motor or widespread functional network based language function (Jacobson et al., 2012). Application of tDCS for aphasia recovery has followed the first two models of neuroplasticity to increase excitability in perilesional and residual left hemisphere areas (Baker et al., 2010; Fridriksson et al., 2011; Marangolo, 2013) and inhibit the overactivation of right hemisphere areas (Monti et al., 2008; You et al., 2011). In comparison to TMS, tDCS is a more recent technology, easily administered, portable, cost-effective and can be simultaneously used with speech-language therapy (Biou et al., 2019).

Along with NIBS, another emerging technology for promoting neuroplasticity in stroke-induced aphasia is electroencephalography-brain computer interface (EEG-BCI). A brain computer interface (BCI) is a device that uses brain activity to operate devices such as computers and prostheses (Wolpaw et al., 2002; van Gerven et al., 2009). Recently, it has been used to detect neural activity for speech and translate it into commands for a speech synthesizer (Brumberg et al., 2010; Rabbani, Milsap, & Crone, 2019). Neural activity is non-invasively measured through electroencephalography (EEG) and transferred to the BCI that aggregates all the EEG detected neural signals, sorts through them, finds the signal of interest, and uses that as a command to instruct a speech generating device (Pitt et al., 2019). EEG technology capitalizes on the models of neuroplasticity by picking up neural potentials from the remaining perilesional brain. This technology is mostly used for communication in locked-in syndrome but has very recently been used to support linguistic communication in individuals with stroke induced non-fluent aphasia (Kleih et al, 2016). In this study, EEG-BCI is used as a method of access to scan and select letters on the screen for copy writing and spelling, thereby the novel technology of EEG-BCI can be categorized as an access method for a high-tech augmentative and alternative communication (AAC) device for individuals with aphasia. High-tech AAC comprises of electronic devices that can be accessed through direct finger touch, switches, hand and body movement, eye tracking, muscular potential estimation and EEG-BCI to instruct a speech generating device for supporting an individual's communication needs.

In the current scoping review, we started with the goal of finding technology (e.g., NIBS and high-tech AAC) that addressed neuroplasticity for linguistic recovery in aphasia, narrowing it down to TMS, tDCS, and EEG-BCI. At the full text review stage, only one high-tech AAC study was found that used EEG-BCI as a tool for directly picking up neural signals for performing a communicative function, leading us to drop the category of high-tech AAC at the full text review stage.

Language recovery using technology

Language recovery in aphasia is a non-linear process with different patterns of neuroplastic recovery over a series of stages classified as acute, subacute, and chronic (Bernhardt et al., 2017; Kiran & Thompson, 2019). Technological intervention such as NIBS can support the neural recovery process from the subacute stage (7 days to 6 months post stroke) where the brain undergoes neurophysiological changes enabling spontaneous recovery to the chronic phase (>6 months) of neurophysiological stability (Cramer, 2008; Teasell et al., 2012). However, NIBS are generally incorporated only during the chronic stage possibly following the long-standing notion that technological intervention meddles with the neurophysiological changes supporting spontaneous recovery in the early stages, thus impeding overall language recovery in stroke induced aphasia (Dietz et al., 2014; Jacobs et al., 2004). As a result, NIBS approaches are often considered only after a speech-language recovery plateau is reached. There is emerging evidence, however, that neurorehabilitation through NIBS can enhance the process of spontaneous recovery and salvage language rehabilitation from the subacute stage leading to a more functional neural reorganization in the chronic stages of recovery (Spielmann et al., 2018b).

The treatment tasks used during application of NIBS approaches and the outcome measures used for evaluating treatment effectiveness vary based on the specific research question, the addressed linguistic domain, aphasia symptoms and severity, and the specific NIBS approach used. Outcome measures refer to specific scales of measurement that are used to evaluate therapeutic progress in objective variables (Salter et al., 2013). Scores from standardized test materials (e.g., Western Aphasia Battery-Revised, Kertesz , 2006; Comprehensive Aphasia Test, Swinburn et al., 2022) have been used to measure speech-language therapeutic progress. In addition, technological measures like electroencephalography (EEG), computed tomography (CT), diffusion tensor imaging (DTI), diffusion weighted imaging (DWI) and structural and functional magnetic resonance imaging (sMRI, fMRI) can provide evidence of treatment-induced neuroplasticity for NIBS approaches (Barwood et al., 2011; Szaflarski et al., 2011). Therefore, the primary research question driving this scoping review was to evaluate utility of NIBS as a therapeutic tool to improve linguistic communication skills in individuals with aphasia. This broad question about utility is answered by understanding the specific details for application of TMS and tDCS during treatment of a language task for different aphasia types and severity.

Method

Search strategy

The first author consulted with a research librarian with experience in evidence synthesis studies to develop the search strategy for this study. The search terms related to the research questions were organized using population, intervention, and outcome from the PICO framework (Schardt et al., 2007). Comparison from the PICO strategic search framework was not included to organize the search strategy, as "comparison" among research studies was not required since each technology and its parameters were different, and the comparison did not improve the quality of this scoping review. The concepts from the PICO framework from this study include: (1) Population-people with aphasia, (2) Intervention- TMS, and tDCS, and (3) Outcome-naming, reading, conversation, linguistic abilities. These concepts were combined to identify relevant literature through a comprehensive search customized for each of these databases- PsycInfo (Proquest), Proquest Dissertations and Theses Global, PubMed, Web of Science, Institute of Electrical and Electronics Engineers (IEEE), Association for Computing Machinery (ACM), and Cochrane Library electronic databases. As addressed above, the initial search, conducted in April 2020, included terms related to high-tech AAC. After eliminating this concept and updating the search to include new research, the final search was conducted in March 2022. The complete search strategy for this study is available in Table 1 of Supplemental Data.

Inclusion/Exclusion Criteria

The review included case reports and observational studies related to individuals with aphasia undergoing treatment paired with NIBS (TMS & tDCS). Initially, this search included publications back to 1995 to 2020. A seminal systematic review on the use of NIBS (Shah-Basak, et al., 2016) for aphasia rehabilitation was found that included studies through 2015 detailing the technical parameters of these technologies for picture naming. Shah-Basak et al., 2016 conducted a metanalyses for articles that used picture naming accuracy as an outcome measure for measuring the effectiveness of NIBS and concluded that TMS improved picture naming accuracy in subacute and chronic post-stroke aphasia whereas tDCS improved picture naming accuracy in chronic population. For the current study, the inclusion criteria were curtailed to studies published from 2015 and focused on a variety of language tasks and outcome measures.

Studies were excluded if: (1) not published in English; (2) not peer-reviewed original research (e.g., systematic reviews, meta-analysis, proposals for randomized controlled trials, editorials); (3) population was not individuals with aphasia (e.g., Alzheimer's disease, traumatic brain injury, amyotrophic lateral sclerosis, neurodegenerative diseases, stroke without aphasia etc.); (4) targeted intervention was not focused on linguistic communication abilities (e.g., focus on motor rehabilitation); (5) targeted technology was used only for assessment (e.g., eye tracking measures for syntactic assessment, computational modeling to inform tDCS montage) and not for rehabilitation.

Selection of studies for review

Studies meeting the search criteria from each database were uploaded into CADIMA software (https://www.cadima.info/index.php) and were independently screened by two reviewers (JK and SS) per the inclusion and exclusion criteria. The conflicts were resolved by a third reviewer (JB). The database search identified 5331 studies and were reduced to 3623 after removal of duplicates. A total of 238 articles met the study criteria after title/abstract review. The full text of these articles was obtained and reviewed to determine eligibility and to sort the studies in a customized data extraction table. Following the review of 238 full-text articles, a total of 57 studies were included where 21 studies used TMS, and 36 studies used tDCS to improve linguistic measures in individuals with aphasia. The process of study selection is also available in Figure 1.

Approach to analysis and synthesis

The current scoping review included experimental studies with varying risks of bias (Chidambaram & Josephson, 2019; El-Gilany, 2018). Information extracted from the eligible studies by two reviewers on separate spreadsheets pertained to the target population,

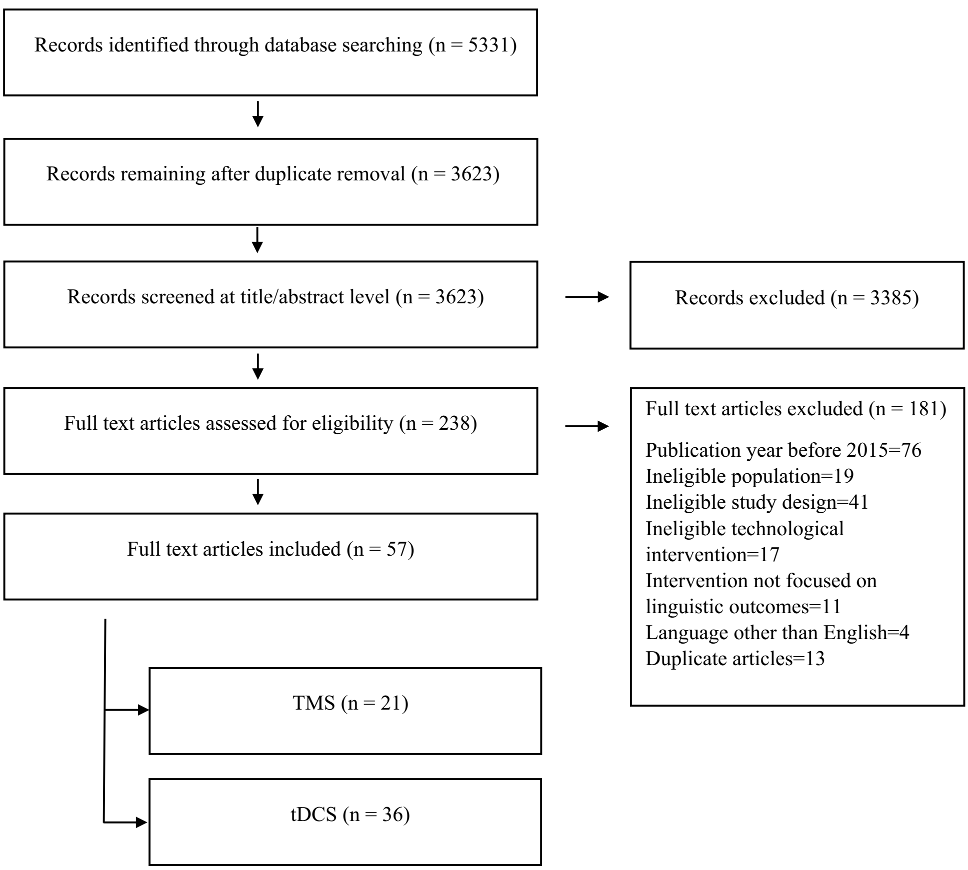

Figure 1. PRISMA (Tricco et al., 2018) flow diagram depicting the study selection process

study design, severity and type of aphasia, description of the technology and its application, period of intervention, language task, and outcome measures, and the main findings. Information from the two spreadsheets was compared and filtered into two tables, one for all the details related to the study design, participants, intervention, and outcome, and one for domain of language and the specific outcome measure worked on in each study for both TMS and tDCS. If information was not identified in the study, then it was reported as missing in the final tables. Data was extracted from the studies in the current review for study characteristics, participant characteristics, intervention details and outcome measures.

Results

The results for the current scoping review as seen in Table 1 are laid out below to understand the specific design and delivery of TMS and tDCS in research settings for improving linguistic outcomes in stroke-induced aphasia.

Study Characteristics

The studies included in this review used experimental study designs (please look at Table 1). Studies with TMS (n = 21) used the following study designs– single subject experimental design (n = 12), and randomized controlled trials (n = 9). Studies with tDCS (n = 36) mainly used crossover experimental design (n = 18) partially or completely allocating participants in a randomized (n = 14) or non-randomized (n = 4) manner. The other study design used in tDCS studies were randomized controlled trials (n = 8), non-randomized controlled trial (n = 1) and single subject experimental design (n = 9). The study design was noted to answer how these technologies are utilized for improving communicative outcomes for people with aphasia in research settings for their eventual transition to clinical practice.

Participant Characteristics

Aphasia type: There were 879 individuals with aphasia participating in the 57 studies included in this review. Studies that mentioned the aphasia type (TMS, n = 18, tDCS, n = 32) largely recruited individuals with non-fluent aphasia (TMS, n = 6, tDCS, n = 13). Broca's aphasia was the most common type of aphasia to be included for remediation through TMS and tDCS (n = 22). Specific classification of aphasia type for participants (e.g., Broca's, Wernicke's, Conduction, Global, Anomia) was reported in TMS (n = 11) and tDCS (n = 17) studies, and in the remaining studies the information had to be interpreted through the lesion size and location. The type of aphasia varied depending on the diagnostic materials used by the researchers.

Aphasia severity: Participants included in studies had mild to severe aphasia. Severity ratings profiles were based on the rating profiles in standardized test materials (e.g., WAB-R, BDAE). Studies with TMS that reported the severity (n = 16) largely included participants with severe aphasia (n = 11). Less than half of studies using tDCS (n = 17) reported aphasia severity of their participants. Some studies (n = 4) reported the severity ratings from

Table 1 :Summary of study design, participant characteristics, intervention, and outcomes details

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Transcranial Magnetic Stimulation										
Vuksanović et al., 2015	Single subject experimental design	1 (M)	63	Chronic	Non-fluent	Severe	iTBS on left Broca's area, cTBS on right homologue of Broca's area	Bilateral TBS (15 sessions)	BNT, BDAE + CT scan	Yes
Yoon et al., 2015	Randomized controlled trial	20 (15M/ 5F)	60.46	Subacute (NE) Chronic (NE)	NE	Moderate	Right IFG	rTMS /20 sessions of 20 minutes each	K-WAB	Yes
Rubi-Fessen et al., 2015	Randomized controlled trial	30 (14M/ 16F	67.9	Subacute (30)	Wernicke's (13) Anomic (7) Global (4) Broca's (6)	Mild to Severe	Right IFG-Brodmann Area 45	rTMS/ 10 sessions of 20 minutes each	AAT, Snodgrass and Vanderwart picture naming inventory	Yes
Zhang et al., 2017	Single subject experimental design	1 (F)	39	Subacute	Conduction	Based on WAB-R scores	Left IFG-Broca's area	HF-rTMS/10 sessions of 20 minutes each	WAB-R + fMRI + DTI	Yes
Harvey et al., 2017	Single subject experimental design	9 (7M/ 2F)	61	Chronic	Non-fluent	Mild to moderate	BA 44, 45, 47 on the right IFG for optimal site finding	rTMS/ 10 sessions of 20 minutes each	BDAE + fMRI	Yes
Haghighi et al., 2017	Randomized controlled trial	12 (5M/ 7F)	55	Subacute	Broca's aphasia (12)	Severe	Inferior posterior frontal gyrus of RH	rTMS/ 10 sessions of 20 minutes each	WAB-R (Farsi version)	Yes
Szaflarski et al., 2018	Single subject experimental design	12 (9M/ 3F)	49	Chronic	Anomic (8) Broca's (2) Global (1) Conduction (1)	Mild to severe	Primary motor cortex in RH	iTBS/10 sessions of 200 seconds each	WAB, BNT, SFT, COWAT +fMRI	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Hu et al., 2018	Randomized controlled trial	40 (24M/ 16F)	46.5	Chronic	Non-fluent	Mild to severe	Mirror area within Broca's area in the uninjured side	Low Frequency - High frequency rTMS/10 sessions of 10 minutes each	WAB (Chinese version)	Yes
Georgiou et al., 2019	Single subject experimental design	2 (1M/ 1F)	61, 39	Chronic	Anomic (1) Global (1)	Moderate Severe	Right pars triangularis	cTBS/ 10 sessions of 40 seconds each	BDAE-SF (Greek version), MAIN, BNT	Yes
Harvey et al., 2019	Single subject experimental design	11 (9M/ 2F)	55.5	Chronic	Broca's (4) Anomic (6) Conduction (1)	Mild to severe	cTBS target - anterior portion of the right hemisphere homologue of Broca's area	cTBS/ 4 sessions of 40 seconds each	Naming (International Picture naming Project Corpus + fMRI	Yes
Ren et al., 2019	Randomized controlled trial	45 (28M/ 18F)	65.95	Subacute	Global (45)	Severe	Right pIFG/pSTG	rTMS/ 15 sessions of 20 minutes each	WAB	Yes
Georgiou et al., 2020	Single subject experimental design	1 (F)	74	Chronic	Global aphasia	Severe	Right PTr of IFG	cTBS/ 40s trains of TBS (600 pulses) for 10 days)	BDAE-SF, BNT (accuracy), PPVT-R,	Yes
Allendorfer et al., 2021a	Single subject experimental design	13 (9M/ 4F)	51.09	Chronic	Global (1) Conduction (1) Wernicke's (1) Broca's (2) Anomic (8)	NE	Left IFG	iTBS/10 sessions of 600 pulses over 200s each	BNT, PPVT, SFT, COWAT, BDAE (Complex ideation subset)	Yes
Allendorfer et al., 2021b	Randomized controlled trial	24 (16M/ 8F)	NE	Chronic	NE	NE	Left IFG	iTBS/15 sessions/ 600 pulses over 200 s	BNT, COWAT, SFT, BDAE (Complex ideation subset), PPVT	Yes
Bai et al., 2021	Randomized controlled trial	30 (13M/ 17 F)	45.3	Chronic	Non-fluent	Severe	Right IFG	rTMS/ 1000pulses for 20 minutes each for 20 days	WAB	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Kranou-Economidou& Kanbanaros, 2021	Single subject experimental design	1 (M)	63	Subacute	Receptive aphasia	Mild	Left DLPFC	iTBS/ 10 sessions for 3 minutes	BDAE-SF, A personal stroke narrative, MAIN, Procedural discourse task	Yes
Szaflarski et al., 2021	Randomized double-blinded Controlled Trial	27(18M/ 9F)	23.1-84.7	Chronic	NE	At least mild aphasia	Residual left IFG	iTBS/ 15 sessions of 10-15 mins each	WAB-AQ, BNT, SFT, COWAT +fMRI	Yes
Chang et al., 2022	Single subject experimental design	5 (3M/ 2F)	45-67	Chronic	Non-fluent	NE	Most activated channel in the Broca, Wernicke, and adjacent area	HF-rTMS/10 sessions	WAB-K (AQ and LQ), K-BNT	Yes
Chou et al., 2022	Randomized, single-blind, sham-controlled study	85 (54M)	60.5	Chronic	Broca (35) Transcortical motor (22) Transcortical mixed (11) Global (17)	NE	Bilateral posterior pars triangularis (PTr), Brodmann area 45	iTBS/10 sessions for 20 mins	CCAT	Yes
Georgiou & Kambanaros, 2022	Single subject experimental design	6 (4M/ 2F)	26-74	Chronic	Global (2) Broca (1) Anomic (4)	Mild (1) Moderate-severe (3) Severe (2)	cTBS- inhibitory rTMS to PTr in right IFG rTMS- right PTr	rTMS/cTBS- 10 sessions of 20 mins each	BDAE-SF, PPVT, GOAT, MAIN	No
Kranou-Economidou & Kanbanaros, 2022	Single subject experimental design	1(F)	31	Chronic	Non-fluent	NE	Left DLPFC	iTBS/ 10 sessions for 3 minutes	BDAE-SF, A personal stroke narrative, MAIN, Procedural discourse task-Shewan spontaneous language analysis	No
Transcranial direct current stimulation (tDCS)										
Wu et al., 2015	Non-randomized controlled trial	12 (10M/ 2F)	43.2	Subacute	Broca's (8) Mixed (2) Conductive (1) Anomic (1)	Severe	Left posterior perisylvian region	Anodal/20 sessions of 20 minutes each	PACA (picture naming and auditory-picture identification) +EEG	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Manenti et al., 2015	Single subject experimental design	1 (F)	49	Chronic	Non-fluent	NE	Anodal over left DLPFC; cathodal over right DLPFC	Bilateral/ 20 sessions of 25 minutes each	AAT, BADA, International Picture-Naming Project Task	Yes
Richardson et al., 2015	Randomized crossover clinical trial	8 (4M/ 4F)	60.63	Chronic	Anomic (3) Broca's (5)	Mild to moderate	Individual optimal montage	HD-tDCS + CS tDCS/10 sessions of 20 minutes each	Naming (Audio+picture matching task), fMRI	Yes
Shah-Basak et al., 2015	Randomized cross over clinical trial	12 (10M/ 2F)	63.6	Chronic	Non-fluent	Moderate	Individual optimal montage	Bilateral/ 10 sessions of 20 minutes each	WAB, sMRI	Yes
Campana et al., 2015	Randomized cross over clinical trial	20 (11M/ 9F)	57.1	Chronic	Non-fluent	NE	Anode- Left inferior frontal gyrus; Cathodal- contralateral frontal polar cortex	Anodal/ 10 sessions of 20 minutes each	Esame del Linguaggio II, fMRI	Yes
Costa et al., 2015	Single subject experimental design	1 (F)	57	Chronic	Non-fluent	Severe	Exp 1 - Anodal – left BA 44/45, cathodal – right BA 44/45 Exp 2 – left BA 39/40	Bilateral/ 3 sessions of 20 minutes each	picture-naming task (pictures from BADA)	Yes
Galletta et al., 2015	Single subject experimental design	1 (M)	43	Chronic	Anomic	Mild	Anode- BA, cathode - contralateral supraorbital region	Anodal/ 10 sessions of 20 minutes each	Sentence Probes- noun and verb retrieval, BNT	Yes
Meinzer et al., 2016	Randomized controlled trial	26 (18M/ 8F)	59.9	Chronic	Broca's (9) Wernicke's (9) Global (6) Amnestic (2)	NE	Anode - left M1, cathode - contralateral supraorbital region	Anodal/ 10 sessions of 20 minutes each	Naming (Standardized battery of pictures n =344)	Yes

(Continued)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Basat et al., 2016	Single subject experimental design	7 (5M/ 2F)	70	Chronic	Anomic (4) Broca's (2)	NE	Left IFG, Right IFG, Left STG, Right STG	anodal and cathodal/ 10 sessions of 10 minutes each	Pictures from SHEMESH stimuli, PALPA, Written Word Association Test, Picture Association Test	Yes
Marangolo et al., 2016	Randomized crossover clinical trial	9 (5M/ 4F)	58.2	Chronic	Non-fluent	NE	anode- ipsilesional left BA, cathode- contralesional IFG	Bilateral/ 15 sessions of 20 minutes each	Esame del Linguaggio II; fMRI	Yes
Santos et al., 2017	Randomized placebo controlled clinical trial	13 (7M/ 6F)	56	Chronic	Anomic (7) Brocas' (6)	NE	right hemisphere, - area homologous to Broca's area	Anodal/ 5 sessions of 20 minutes each	BNT	No
Keser et al., 2017	Randomized crossover clinical trial	10 (4M/ 6F)	56.4	Chronic	Broca's (9) TCM (1)	NE	Right IFG; reference electrode - contralateral supraorbital region	Anodal/ 1 session of 20 minutes	WAB-R AQ and LQ	Yes
Darkow et al., 2017	Randomized crossover clinical trial	16 (10M/ 6F)	56.7	Chronic	NE	Mild	anode – left MC; return electrode - right supraorbital region	Anodal /1 session of 20 minutes	Snodgrass and International Picture Naming Project, fMRI	No
De Tomasso et al., 2017	Single subject experimental design	1 (M)	58	Chronic	Non-fluent	NE	anodic - left parietal area, cathodic - right homologue area	Dual tDCS/ 12 sessions of 20 minutes	AAT, BADA	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Norise et al., 2017	Sham-controlled partial cross over design	9 (7M/ 2F)	62	Chronic	Non-fluent	Mild to severe	either the anode or cathode over left frontal lobe or right frontal lobe	Bilateral/ 10 sessions of 20 minutes each	BDAE - speech fluency	Yes
Sebastian et al., 2017	Randomized crossover clinical trial	1 (M)	57	Chronic	Non-fluent	Severe	Anode - right cerebellum, Cathode - right deltoid muscle	Cerebellar tDCS/ 15 sessions of 20 minutes each	Written spelling (using words from John Hopkins Dysgraphia Battery) PNT, fMRI	Yes
Branscheidt et al., 2018	Randomized crossover clinical trial	16 (12M/ 4F)	61.1	Chronic	Broca's (5) Amnestic (6) Global (1)	NE	Anode - left MC; reference electrode - right supraorbital region	Anodal/ 1 session of 20 minutes	Lexical decision task (using German verbs and nouns)	Yes
Fridriksson et al., 2018	Randomized clinical trial	74 (52M/ 22F)	60	Chronic	Broca's (39) TCM (1) Global (3) Wernicke's (5) Conduction (15) Anomic (11)	Based on WAB-R scores	Mean location of stimulation - TPJ, cathodal - right supraorbital head region	Anodal/ 15 sessions of 20 minutes each	PNT + naming 80	Yes
Sandars et al., 2018	Single subject experimental design	1 (M)	81	Chronic	Broca's (1)	NE	perilesional anodal, perilesional cathodal, perilesional sham, contralesional anodal, contralesional cathodal,	Bilateral/ 24 sessions of 20 minutes each	Naming (International Picture Naming Project), picture description task (cookie theft)	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Marangolo et al., 2018	Randomized crossover clinical trial	12 (6M/ 6F)	57.75	Chronic	Non-fluent	Mild	Cathode on the right cerebellar cortex	Cerebellar tDCS-/ 20 sessions of 20 minutes each	Naming accuracy on verbs and nouns	Yes
Spielmann et al., 2018a	Randomized crossover clinical trial	58 (40M/ 18F)	57.9	Subacute	Fluent (30) Non-fluent (20) Mixed (8)	Based on test scores	Anode on left IFG (F5) and cathode on supraorbital region(Fp2)	Anodal/ 5 sessions of 20 minutes each	BNT, Aphasia Severity Rating Scale, ANELT	Yes
Spielman et al., 2018b	Randomized crossover study	13 (10M/ 3F)	53.15	Chronic	Non-fluent (6) Fluent (7)	Mild to severe	anodal - left IFG or left STG; cathode - contralateral supraorbital region	Anodal/ 3 sessions of 20 minutes each	Naming (pictures of nouns from European Data Bank)	Yes (for trained items)
Silva et al., 2018	Randomized controlled trial	14 (8M/ 6F)	52.38	Chronic	Broca's (6) Anomic (8)	Mild to moderate	Anode - left supraorbital region, cathode - RH area homologous to BA	Cathodal/ 5 sessions of 20 minutes each	BNT - short version, Snodgrass and Vanderwert Test	Yes
Pestalozzi et al., 2018	Single subject experimental design	14 (7M/ 7F)	57.4	Chronic	Anomic (6) Conduction (4) Broca's (3) Global (1)	NE	Anode - left DLPFC, Cathode- right supraorbital area	Anodal/ 2 sessions of 20 minutes	Picture naming task (pictures in French database), phonemic fluency task, repetition task (LEXIQUE database, fMRI	Yes
Feil et al., 2019	Randomized controlled trial	12 (10M/ 2F)	NE	Subacute	Non-fluent	Moderate	Anode - IFG (F5)	Bilateral/ 10 sessions of 20 minutes	AAT, BNT, ANELT	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Fiori et al., 2019	Crossover clinical trial	20 (12M/ 8F)	63	Chronic	Non-fluent	NE	cathode - right homolog of BA, 4 anodes - 3.5 cm from cathode	Cathodal HD tDCS/ 10 sessions of 20 minutes each	Verb retrieval task	Yes (only after cathodal HD-tDCS at 2mA)
VilaNova et al., 2019	Crossover clinical trial	12 (6M/ 6F)	57.6	Chronic	Transcortical (2) Broca's (5) Anomic (4) Conduction (1)	NE	Anodal - Left BA, cathode - right supraorbital area	Anodal/ 10 sessions of 20 minutes	Snodgrass test, syllable repetition	No
Buchwald et al., 2020	Single subject experimental design	1 (M)	60	Chronic	Broca's	Severe	Anode (T7) cathode(F4)	Anodal/9 sessions of 20 min	Naming and speech production accuracy, fMRI	Yes
Guillouet et al., 2020	Randomized crossover clinical trial	14 (10M/ 4F)	53.8	Subacute (6) Chronic (4)	Mixed (3) Broca (4) Wernicke (1) Anomic (1) TCM (3) Conduction (2)	NE	Anodal on IFG, Cathode - contralateral IFG	Bilateral/ 10 sessions of 20 minutes each	HDAE	No
Hashim et al., 2020	Single subject experimental design	5	54-78	Chronic	Expressive (4) Mixed Transcortical (1)	NE	F3	Anodal/10 session for 20 mins each	Naming	Yes
Ihara et al., 2020	Crossover	6(5M/ 1F)	50-78	Chronic	Wernicke (4) Anomic (1) Mixed (1)	NE	anode - left BA, cathode - right orbitofrontal cortex	Anodal -2 sessions for 20 mins each	Naming and sentence production using pictures from a Japanese database	Yes
Sebastian et al., 2020	Randomized within-subject crossover study	21 (18M/ 3F)	37-79	Chronic	NE	BDAE Severity Percentile	active electrode - right cerebellar cortex, reference - right shoulder	Cerebellar (anodal/ cathodal)/ 15 sessions of 20 mins	Naming 80 Test PNT, MRI	Yes

(*Continued*)

Table 1 (Continued).

Citation	Study Design	N	Mean Age (years)	Stage of recovery (Subacute/ chronic)	Type of aphasia	Severity of aphasia	Region of stimulation	Subtype and duration of stimulation	Outcome measures	Language improvement
Cherney et al., 2021	Randomized Clinical Trial	12 (8M/ 4F)	46.1-71.1	chronic	NE	NE	MFG/FP/M1/SMG/ IFG	Anodal/Cathodal- 30 sessions of 13 mins	WAB-R AQ and LQ, NORLA, fMRI	Yes
Pisano et al., 2021	Randomized crossover design	14(7M/ 7F)	55-65	Chronic	Non-fluent	Severe	anodal and cathodal current simultaneously placed over the left and right temporo-parietal cortex	Dual tDCS/ 10 sessions of 20 mins	Esame del Linguaggio II	Yes
Soliman et al., 2021	Randomized clinical trial	19(13M/ 6F)	52.58	Sub-acute	Broca (7) Global (12)	NE	Anodal- left BA, Cathode- right BA	Bilateral/ 10 sessions of 20 min each	Hemispheric stroke score-language score, MRI, DTI	Yes
Zhao et al., 2021	Randomized clinical trial	18(2M/ 16F)	58	Subacute	NE	NE	Anode- Left IFG, Cathode - deltoid muscle of right shoulder	Anodal/ 20 sessions of 20 min each	WAB- AQ	Yes

BA= Brodmann Areas, BA= Broca's area, CS-tDCS= Conventional Sponge Transcranial Direct Current Stimulation, CT= Computed Tomography, cTBS= continuous Theta Burst Stimulation, DLPFC= Dorsolateral PreFrontal Cortex, DTI= Diffusion Tensor Imaging, EEG-BCI = Electroencephalography-Brain Computer Interface, fMRI= functional Magnetic Resonance Imaging, F= Female, FP=Frontal Pole, HD-tDCS= High- definition Transcranial Direct Current Stimulation, iTBS= intermittent Theta Burst Stimulation, IFG= Inferior Frontal Gyrus, M= Male, MC= Motor Cortex MN= Mixed Non-Fluent, N= Number of participants with aphasia, NE= not specified, PTr= pars triangularis, rTMS= repetitive Transcranial Magnetic Stimulation, sMRI= structural Magnetic Resonance Imaging, STG= Superior Temporal Gyrus, SMG= Supramarginal Gyrus, TCS= Transcortical Sensory, TCM=Transcortical Motor, TPJ= Temporal-parietal junction standardized tests with interpretation left to readers. Studies with tDCS that mentioned severity recruited participants with mild (n = 7), moderate (n = 4), and severe aphasia (n = 7).

Stage of recovery: The stage of recovery mentioned in all the included studies was either subacute or chronic. Among the final selected 57 research studies, there were 12 studies that had participants during the subacute stage of recovery and 47 studies that included participants during the chronic stage of recovery. Overall, incorporation of NIBS was seen to be prevalent during the chronic stage of recovery. There was a total of 21 TMS studies with 6 studies including participants during subacute stage and 16 studies recruited participants during chronic stage of stroke. As for the 37 tDCS studies, 6 studies had subacute participants and 31 studies had chronic participants.

Intervention details

Types of stimulation: TMS can be implemented as low frequency rTMS (n = 8), high frequency rTMS (n = 2), both low and high frequency rTMS (n = 1), iTBS (n = 7), cTBS (n = 4), and both iTBS and cTBS (n = 1). There is a gradual transition seen in older studies largely using inhibitory low frequency rTMS to recent studies using stimulatory iTBS. On the other hand, tDCS can be administered as unilateral anodal (n = 24), unilateral cathodal (n = 7), bilateral (n = 7), high definition (HD) (n = 2), and cerebellar (n = 3). In the current review, unilateral anodal stimulation (excitatory) emerged as the most used stimulation pattern because neural reorganization of the left hemispheric perilesional areas as in the first model of neuroplasticity has support in the literature as the optimal mechanism of neuroplastic changes for language recovery (Shah et al., 2013).

Duration and timing of stimulation: Studies with TMS largely included 10-20 sessions of 20-minute stimulation each followed by 30- to 45-minute speech-language therapy. TMS stimulation is used as an adjunct to conventional speech-language therapy and can be used to 'prime' the brain for therapy (Kim et al., 2006; Smith & Stinear, 2016). Studies with tDCS had a variable range of sessions from 1 to 30 but largely, studies included 10 sessions of 20 minutes each either prior to or in conjunction with 45-minute speech-language therapy sessions.

Site of stimulation: The site of stimulation for both TMS and tDCS focused on left perilesional areas or right hemisphere homologous areas. Studies with TMS stimulated portions of left inferior frontal gyrus (n = 8), left dorsolateral prefrontal cortex (n = 2), portions of right inferior frontal gyrus (n = 11), right superior temporal gyrus (n = 1), right primary motor cortex (n =1). Inhibitory stimulation of right hemisphere areas was the most common type of stimulation seen in TMS studies following the second model of neuroplasticity focusing on the maladaptive compensatory recruitment of the right hemisphere areas. Studies with tDCS focused on amplifying the current flow through the perilesional tissue by stimulating areas of left inferior frontal gyrus (n = 15), left perisylvian areas (n = 4), left areas of motor cortex (n = 5), left sensory cortex (n = 5) and right cerebellar cortex (n = 3) while inhibiting the activity in right inferior frontal gyrus (n = 10), motor cortex (n = 2) and superior temporal gyrus (n = 1).

Intensity of stimulation: Studies using inhibitory low frequency rTMS delivered it at 1 Hz, 1200 pulses for 20 minutes citing the interhemispheric inhibition hypotheses sometimes followed by speech-language therapy (Harvey et al., 2017; Ren et al., 2019; Zhang et al., 2017). Bilateral theta burst stimulation (TBS) can be applied with 600 intermittent TBS (iTBS, Szaflarski et al., 2018) pulses in 200 seconds and 600 continuous TBS (cTBS, Vuksanović et al., 2015) pulses in 40 seconds. cTBS has also been applied to the right hemisphere in a format of 50 Hz triplets of TMS pulses at 5 Hz, 600 pulses in 40 seconds (Georgiou et al., 2019; Harvey et al., 2019). The frequency of iTBS and cTBS stimulation is based on the duration and type of stimulation. Alternatively, studies using tDCS with any type of stimulation varied the current intensity between 1 mA to 2 mA of current for 20 minutes (Pestalozzi et al, 2018; Sebastian et al., 2020).

Outcome measures

The outcome measures for evaluating effectiveness of these technological approaches as a therapeutic tool included task-related behavioral assessment measures, standardized test scores, and neuroimaging measures. Studies using TMS largely used standardized test scores (n = 18) accompanied by specific training task related measures (n = 4) and neuroimaging measures (n = 6). Studies with tDCS combined the three measures with primary usage of task related outcome measures (n = 19) followed closely by scores of standardized test materials (n = 16) with some studies also using neuroimaging measures (n = 9). Standardized test materials and task related scores (e.g., pictures from International Picture Naming Project were used during baseline and treatment, Harvey et al., 2019) can measure treatment induced behavioral progress while neuroimaging measures can offer a peek in neuroplastic changes (Hartwigsen & Saur, 2019). Specifically, almost one third (7/21) of the TMS studies, and one fourth (9/36) of the tDCS studies used a neuroimaging measure for evaluating pre-post treatment neural recovery.

Discussion

The purpose of the current scoping review was to evaluate the use of NIBS as therapy aids for improving linguistic outcomes by targeting neural recovery in individuals with aphasia. The points of investigation were study design; type and severity of aphasia, stage of recovery; type, duration, timing, site, and intensity of stimulation; and treatment effectiveness outcome measures. The results from this scoping review indicate that different combinations for stimulation through TMS and tDCS are being encouraged to work on recovery in specific language domains in individuals with stroke-induced aphasia as seen in Table 2.

Study Design

Randomized controlled trials limit the bias and present an effective way to measure the efficiency of treatment (Akobeng, 2005; Hariton & Locascio, 2018). Studies with TMS that used randomized controlled trials randomly categorized participants into two groups and the experimental group received TMS with speech-language therapy and control group received only speech-language therapy. Studies with tDCS largely used cross over clinical trials where the two groups of participants underwent the same intervention at different time points in the study. Cross over clinical trials are advantageous as the subjects can act as their own controls thus requiring lesser number of participants (Sills & Brodie, 2009). Studies involving TMS and tDCS did follow-up evaluations after a washout period ranging from one week to months (Allendorfer et al., 2021a; Buchwald et al., 2020). The few differences in research design like the selection of participants, overall duration, and timing of treatment, can be attributed to the specific mechanism and manner of application for TMS vs tDCS. Naming and comprehension was the largely worked upon language domain in each of these studies using either randomized controlled trials or single subject designs. The study design for each of these studies was noted to help with NIBS application in clinical practice. Based on the current review, single subject experimental design is increasingly being used in research settings and can be easily adapted in clinical setting where SLPs can evaluate treatment effectiveness for specific language tasks (e.g., spontaneous speech, verbal fluency) at strategic timepoints (Byiers, Reichle, & Symons, 2012; Horner et al., 2005; Kazdin, 2011).

Participant Characteristics

Studies with both TMS and tDCS recruited participants with all aphasia types and severity as seen in Table 1. However, individuals with non-fluent chronic severe aphasia were maximally recruited. In the following sections, NIBS characteristics for individuals with non-fluent chronic severe aphasia are discussed. The readers are requested to please look at Table 1 for concluding NIBS specifics for the different aphasia types and severity. For individuals with chronic non-fluent severe aphasia, TMS stimulation (whether low frequency rTMS or cTBS) focused on inhibiting the activity of right hemisphere and promoting the left hemisphere perilesional areas (Chang et al., 2022; Hu et al 2018; Vuksanović et al., 2015). Bilateral stimulation through TMS types following third model of neuroplasticity is aimed at curbing activity in right hemisphere to promote activation in perilesional left hemisphere regions. The language domain worked in TMS studies with non-fluent chronic aphasia was comprehension of words and commands, picture naming, verbal fluency, and discourse (Bai et al., 2021; Chang et al., 2022; Harvey et al., 2017; Hu et al., 2018; Kranou-Economidou & Knabanaros, 2021)

Studies using tDCS focused on bilateral stimulation of left and right hemispheres in individuals with chronic non fluent aphasia (Costa et al., 2015; De Tomasso et al., 2017; Pisano et al., 2021). This tDCS bilateral stimulation also follows the third model of neuroplasticity where perilesional areas in the left hemisphere are stimulated and homologous areas in the right hemisphere are moderately curbed to promote efficient use of the residual brain tissue in both hemispheres for achieving language outcomes (Manenti et al., 2015; Marangolo et al., 2016; Shah-Basak et al 2015). Studies with bilateral tDCS stimulation for non-fluent chronic aphasia largely focused on picture naming but also on repetition, fluency, and writing (De Tomasso et al., 2017; Marangolo et al., 2016; Pisano et al., 2021).

In studies with TMS, participants included were in both subacute and chronic stages of recovery possibly because TMS is a widely available tool in clinical neurology and has been used for treatment of neuropsychological disorders for a longer period (Basil et al., 2005; Galletta et al., 2011; Rossi et al., 2009). In studies with tDCS, lesser studies included participants during subacute recovery which may reflect the limited success of tDCS in improving communicative outcomes in subacute cases (Shah-Basak et al., 2015; Shah-Basak et al., 2016).

To conclude, participants in the studies using NIBS recruited adults with mild to severe, largely non-fluent type, chronic stage of aphasia to improve their naming and comprehension skills. However, specific information about the type, severity, and stage of stroke recovery of the participants (as given in Table 1) combined with the language task information (in Table 2) with respect to the neuromodulation measure used can help clinicians in their decision-making process of which technology and stimulation area would suit their client and be compatible with their speech-language therapy program (Awosika & Cohen, 2019).

Intervention details

Transcranial Magnetic Stimulation: For studies involving individuals with chronic non fluent aphasia, a combination of right hemisphere inhibition and left hemisphere activation through bilateral TMS, low frequency rTMS to the right hemisphere, high frequency rTMS to the left hemisphere, and left iTBS was used for improving comprehension, naming, repetition, and verbal fluency (Allendorfer 2021a,2021b; Hu et al., 2018; Turkeltaub et al., 2011; Zhang et al., 2017). As for the duration of TMS stimulation, rTMS for 20 minutes and TBS for 200 seconds can be administered prior to speech language therapy (Bai et al., 2021; Georgious & Kambanaros, 2022; Ren et al., 2019; Szaflarski et al., 2018, 2021).

The site of stimulation for individuals with chronic non-fluent aphasia receiving TMS stimulation through rTMS or iTBS was left and right inferior frontal gyrus (Bai et al., 2021; Szaflarski et al., 2021; Yoon et al., 2015). The intensity of stimulation for TMS application is based on the type of stimulation: low frequency rTMS-1Hz, high-frequency rTMS- 5Hz with 1200 pulses whereas for TBS: 50Hz 600 intermittent pulses in 200s and 600 continuous pulses in 40s. Thus, a combination of bilateral rTMS stimulation with a focus on stimulating the functional connectivity between perilesional left hemisphere areas and right hemisphere homologues can be used for language rehabilitation in aphasia (please refer to Table 1 and 2 for specific clinical parameters). Nineteen out of the 21 TMS studies included in this review showed that application of TMS improved language outcomes.

Transcranial Direct Current Stimulation: Studies using tDCS for chronic non-fluent aphasia mainly used bilateral stimulation of left and right hemispheres for naming, comprehension, repetition, writing, and discourse even though unilateral anodal stimulation was the most commonly used tDCS modulation in the current scoping review (Costa et al., 2015; De Tomasso et al., 2015; Fiori et al., 2019; Manenti et al., 2015; Marangolo et al., 2016, Norise et al., 2017; Pisano et al., 2021). The duration of all types of tDCS stimulation was about 20 minutes (Pisano et al 2021; Sebastian et al 2020; silva et al., 2018; Soliman et al., 2021, Zhao et al., 2021). Bilateral tDCS and other types of tDCS can be applied either 20 minutes before or simultaneously for the first 20 minutes in a 45minute to 1-hour speech-language therapy session (Costa et al., 2015; Feil et al., 2019; Marangolo et al., 2016). Thirty-two out of 36 studies using tDCS stimulation showed an improvement in language outcomes for its participants.

The site of stimulation in tDCS studies is based on the remaining perilesional tissue and how it can conduct current between the two saline soaked sponges (Awasika & Cohen, 2019). The optimal electrode montage in tDCS studies can be identified through initial placement of electrodes in frontal areas (e.g., F3 and F4 according to the international 10-20 EEG measurement system) in early training sessions for a task (e.g., picture naming) by evaluating which particular montage results in greatest post-stimulation accuracy in task measures and neuroimaging measures (Lifshitz Ben Basat et al., 2016; Norise et al., 2017; Shah-Basak et al., 2015). Additionally, current flow to target area can be initially assessed through computational modeling for montage selection (Themistocleous et al., 2021). Electrode placement in bilateral tDCS stimulation refers to when the excitatory anode is placed on left Broca's area and the inhibitory cathode is placed on the contralesional right homologue of Broca's area (Costa et al., 2015; Feil et al., 2019; Manenti et al., 2015; P. Marangolo et al., 2016).

The intensity of current in bilateral stimulation for chronic non-fluent aphasia was 2mA (Marangolo et al, 2016; Manenti et al., 2015; Norise et al., 2017; Pisano 2021; Shah-Basak t al., 2015). The flow of the same amplitude of current can be increased using HD-tDCS, which is a variable electrode montage from conventional tDCS, using a ring of small electrodes in place of large pads (Villamar et al., 2013). A 4 X 1 HD-tDCS montage involves four small return electrodes arranged in a circle around a central electrode placed on the target area. The strength of the generated electric field is maximum under the central electrode as the current is constrained by the outer ring of electrodes, thus reducing the extent of the electric field, and amplifying the intensity of current in comparison to conventional electrodes places across the head. Another way of electrode placement is cerebellar tDCS, where anodal and cathodal stimulation of the right cerebellum has been found to modulate language fluency in healthy individuals (Pope & Miall, 2012; Turkeltaub et al., 2016) and individuals with aphasia (Sebastian et al., 2020; Sebastian et al., 2017). Stimulation of the right cerebellum produces an electric field that can transmit to the left cerebrum through intact neural pathways (Wessel & Hummel, 2018). Conclusively, tDCS can be administered by first identifying the area of stimulation, selecting the electrode montage through current modelling, the type of tDCS, and then its application before or simultaneously with speech-language therapy.

Outcome measures

For studies with non-fluent chronic individuals with aphasia undergoing speech language therapy accompanied by TMS or tDCS, scores from standardized test material were used to measure treatment induced linguistic changes (please look at Table 2 for specific language domain based outcome measures). Along with standardized test material, studies with TMS used CT and fMRI to assess treatment induced neurobiological changes (Harvey et al., 2017, 2019; Szaflarski et al., 2018; Vuksanović et al., 2015; Zhang et al, 2017). Studies with tDCS used both scores from standardized tests and task-related behavioral outcome measures (please look at Table 2) and then combined it with EEG, sMRI, and fMRI for treatment induced neural changes (Buchwald et al., 2020; Campana et al., 2015; Cherney et al, 2021; Pestalozzi et al., 2018; Richardson et al., 2015; Sebastian et al., 2017; Wu et al., 2015). Studies with NIBS often use neuroimaging measures to first evaluate the site of stimulation and secondly to objectively measure neural reorganization correlating them with behavioral outcomes, thus forming

Table 2 :Summary of language domain and outcome measures

Domain	Measurement tests	Studies
Language		
Comprehension	Hemispheric Stroke Scale (HSS)-Arabic version	Soliman et al.,2021
	CCAT	Chou et al., 2022
	K-WAB, WAB, WAB-R	Yoon et al., 2015; Haghighi et al., 2017; Zhang et al., 2017; Hu et al., 2018; Ren et al., 2019; Bai et al., 2021; Shah-Basak et al., 2015; Keser et al., 2017; Zhao et al., 2021
	AAT	Manenti et al., 2015; Rubi-Fessen et al., 2015; De Tamasso et al., 2017; Feil et al., 2019
	BADA	Manenti et al., 2015
	PACA	Wu et al., 2015
	BDAE	Vuksanovic et al., 2015; Georgiou et al., 2019; 2020; Allendorfer et al., 2021a, b; Kranou-Economidou & Kanbanaros, 2021; Georgiou & Kambanaros, 2022
Spontaneous speech	HDAE (different nouns,verbs,adjectives,adverbs, pronouns)	Guillouet et al., 2020
	BDAE	Norise et al., 2017
	WAB-R	Yoon et al., 2015; Zhang et al., 2017; Hu et al., 2018; Ren et al., 2019; Shah-Basak et al., 2015; Keser et al., 2017
Naming	Hemispheric Stroke Scale (HSS)-Arabic version	Soliman et al.,2021
	Naming 80 Test	Fridriksson et al., 2018; Sebastian et al., 2020
	PNT	Fridriksson et al., 2018; Sebastian et al., 2020
	BDAE	Harvey et al., 2017; Hashim et al., 2020
	GOAT	Georgiou & Kambanaros, 2022
	BNT, K-BNT	Vuksanovic et al., 2015; Szaflarski et al., 2018; Georgiou et al., 2019; 20; Allendorfer et al., 2021a, b; Szaflarski et al., 2021; Galletta et al., 2015; Santos et al., 2017; Silva et al., 2018; Feil et al., 2019; Chang et al., 2022
	Esame del Linguaggio II (oral noun and verb naming)	Campana et al., 2015; Marangolo et al., 2016; Pisano et al., 2021
	K-WAB; WAB (Chinese), WAB, WAB-R	Shah-Basak et al., 2015; Zhao et al., 2021
	Naming accuracy (Standardized battery of pictures, pictures from SHEMESH stimuli; pictures from japanese database)	Yoon et al., 2015; Hu et al., 2018; Haghighi et al., 2017; Zhang et al., 2017; Ren et al., 2019; Bai et al., 2021; Richardson et al., 2015; Basat et al., 2016; Meinzer et al., 2016; Marangolo et al., 2018; Buchwald et al., 2020; Ihara et al., 2020
	Snodgrass test; Snodgrass and Vanderwart picture naming inventory	Rubi-Fessen et al., 2015; Darkow et al., 2017; Silva et al., 2018; VilaNova et al., 2019
	Verb retrieval Task	Fiori et al., 2019
	AAT	Manenti et al., 2015; Rubi-Fessen et al., 2015; Feil et al., 2019
	Picture naming task (BADA); french database	Costa et al., 2015; Pestalozzi et al., 2018; Spielman et al., 2018b
	BADA; International picture-naming Project Task	Harvey et al., 2017; 2019; Manenti et al., 2015; Sander et al., 2018
	PACA	Wu et al., 2015
Repetition	Hemispheric Stroke Scale (HSS)-Arabic version	Soliman et al.,2021;
	CCAT	Chou et al., 2022
	BDAE	Vuksanovic et al., 2015; Georgiou et al., 2019; 2020;
	WAB, WAB-R, K-WAB	Yoon et al., 2015; Zhang et al., 2017; Hu et al., 2018; Ren et al., 2019; Shah-Basak et al., 2015; Keser et al., 2017; Zhao et al., 2021
	Esame del Linguaggio II (word/nonword repetition)	Marangolo et al., 2016; Pisano et al., 2021
	Syllable repetition	VilaNova et al., 2019
	AAT	Manenti et al., 2015; Rubi-Fessen et al., 2015; De Tamasso et al., 2017; Feil et al., 2019
	Repetition task	Pestalozzi et al., 2018
	BADA	De Tamasso et al., 2017

(*Continued*)

Table 2 (Continued).

Verbal fluency	Hemispheric Stroke Scale (HSS)-Arabic version	Soliman et al.,2021
	WAB, WAB-R	Haghighi et al., 2017; Zhao et al., 2021
	COWAT	Szaflarski et al., 2018; Allendorfer et al., 2021a, b; Szaflarski et al., 2021
	BDAE	Vuksanovic et al., 2015
	Phonemic fluency task	Pestalozzi et al., 2018
	SFT	Szaflarski et al., 2018; Allendorfer et al., 2021a, b; Szaflarski et al., 2021
Discourse	Picture description; BDAE (cookie theft), Esame del Linguaggio II	Campana et al., 2015; Vuksanovic et al., 2015; Marangolo et al., 2016; Norise et al., 2017; Sanders et al., 2018
	MAIN	Georgiou et al., 2019; Kranou-Economidou & Kanbanaros, 2021; Georgiou & Kambanaros, 2022
	A Procedural Discourse Task; A personal stroke narrative	Kranou-Economidou & Kanbanaros, 2021
Reading	BDAE	Georgiou et al., 2019; 2020; Kranou-Economidou & Kanbanaros, 2021; Georgiou & Kambanaros, 2022; Hashim et al., 2020;
	CCAT	Chou et al., 2022
	ORLA, NORLA-6	Cherney et al., 2021
	Esame del Linguaggio II (word/nonword reading)	Marangolo et al., 2016; Pisano et al., 2021
	WAB	Keser et al., 2017; Cherney et al., 2021
	AAT	De Tamasso et al., 2017
	BADA	De Tamasso et al., 2017
Writing	Esame del Linguaggio II	Pisano et al., 2021
	BDAE	Georgiou et al., 2019; Kranou-Economidou & Kanbanaros, 2021; Georgiou & Kambanaros, 2022
	CCAT	Chou et al., 2022
	AAT	Manenti et al., 2015; Rubi-Fessen et al., 2015; De Tamasso et al., 2017; Feil et al., 2019
	PNT; Johns Hopkins dysgraphia battery	Sebastian et al., 2017
	BADA	De Tamasso et al., 2017
	K-WAB, WAB-R	Yoon et al., 2015; Keser et al., 2017
Receptive vocabulary	PPVT, PPVT-R	Georgiou et al., 2020; Allendorfer et al., 2021b; Georgiou & Kambanaros, 2022
Sentence production	Sentence -noun and verb probes	Galletta et al., 2015; Buchwald et al., 2020; Ihara et al., 2020
	BDAE (cookie theft)	Norise et al., 2017
	WAB (story retell)	Bai et al., 2021
Lexical decision	BADA	De Tamasso et al., 2017
	German verbs	Branscheidt et al., 2017
Dictation	Esame del Linguaggio II (word/non-word dictation)	Pisano et al., 2021
Communication	ANELT	Spielmann et al., 2018a; Feil et al., 2019
	Aphasia Severity Rating Scale	Spielmann et al., 2018a

AAT- Aachen Aphasia Test, ANELT- Amsterdam-Nijmegen Everyday Language Test; BADA- Battery for the Analysis of the Aphasic Deficit; BNT- Boston Naming Test; BDAE- Boston Diagnostic Aphasia Examination; CCAT- Concise Chinese Aphasia Test; COWAT- Controlled Oral Word Association Test; GOAT- The Greek Object and Action Test; HDAE - French adaptation of the Boston Diagnostic Aphasia Examination; IPNP- International Picture Naming Project database; WAB-R - Western Aphasia Battery; MAIN- The Multilingual Assessment Instrument for Narratives NORLA- Naming and Oral Reading for Language in Aphasia 6-point scale; ORLA- Oral Reading for Language in Aphasia; PACA- Psycholinguistic Assessment in Chinese Aphasia; PNT - Philadelphia Naming Test; PPVT- The Peabody Picture Vocabulary Test–Revised; SFT: Semantic Fluency Test a clearer picture of therapy induced changes (Arthurs & Boniface, 2002; Sejnowski, Churchland, & Movshon, 2014). Specific information for intervention and outcome details can be found in Table 1 and 2.

Limitations

There was lack of consistency between the research design and methodology of the included studies for a precise comparative discussion of technological effectiveness. Based on the technology, there were differences in the design and the duration and manner of application of each technology as well. These differences, however, do not take away from the global relevance of TMS and tDCS facilitating neural reorganization in post-stroke aphasia recovery. In addition, most of the studies included in this review lacked specific mention of the type and severity of aphasia, which will be needed in the future to develop individualized tailor-made programs based on the site of lesion and symptoms of the participant.

Conclusion

Stroke-induced aphasia leads to long-term difficulties in communication and depreciation in the quality of life. Novel technological approaches in heterogenous studies like those mentioned in this scoping review present potential therapeutic tools to improve communicative outcomes in individuals with stroke-induced aphasia from the early (subacute) through late (chronic) stages of recovery. The evidence from this scoping review suggests novel technological approaches can be a useful tool to support individuals in having a better quality of life with TMS determining lesions and causality and tDCS supporting post-stroke neuroplasticity. Several combinations of TMS and tDCS stimulation in these research studies speak to a need for developing standardized models of intervention for each technology and language domain to guide clinicians, patients, caregivers, and bioengineers in the clinical decision-making process.

Disclosure Statement

The authors report no conflict of interest.

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