Behavioural Brain Research 438 (2023) 114165

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Effects of transcranial electrical stimulation techniques on foreign vocabulary learning

Yolanda Balboa-Bandeira, Leire Zubiaurre-Elorza, M. Acebo García-Guerrero, Naroa Ibarretxe-Bilbao, Natalia Ojeda, Javier Peña *

Department of Methods and Experimental Psychology, Faculty of Health Sciences, University of Deusto, Bilbao, Spain

ARTICLE INFO

Keywords:
Transcranial electrical stimulation (tES)
TDCS
TRNS
Foreign language learning

ABSTRACT

Although the use of transcranial electrical stimulation (tES) techniques on healthy population has been linked to facilitating language learning, studies on their effects on foreign language learning processes are scarce and results remain unclear. The objective of this study was to analyze whether tES enhances foreign language learning processes. Sixty-four healthy native Spanish-speaking participants were randomly assigned to four groups (transcranial direct current, transcranial random noise, tDCS-tRNS stimulation, or sham). They completed two intervention sessions with a two-week gap in between. During the first session the participants received stimulation (1.5 mA) while learning new English words and then performed recall and recognition tasks. Learning was assessed at follow-up, two weeks later. No differences in learning between groups were observed in the first session ($F_{(1,61)}$= .86; p = .36). At follow-up, significantly higher learning accuracy was observed after tRNS compared to sham (p = .037). These results suggest that tRNS could be helpful in improving the processes involved in foreign language vocabulary learning.

1. Introduction

Spoken language is one of the main forms of communication used by human beings to interact with each other. Nowadays, fluency in one or more foreign languages has become commonplace in many parts of the world, with an increasing number of people being bilingual or multilingual. In addition, proficiency in another language can bring many benefits and advantages. It helps people to overcome the language barrier traveling to other countries; it also provides greater opportunities for promotion or improvement at work [32]. Several studies have shown that learning other languages also has health benefits, such as improvement in different cognitive areas [50], or the delay of the onset of dementia symptoms [9]. In addition, neuroimaging studies have reported an increase in the volume and thickness of certain parts of the brain (hippocampus and cerebral cortex), as well as strengthened neural connections while learning a foreign language [12,51]. In contrast, there is also evidence that bilingualism may have some disadvantages or downsides. The most prominent disadvantages of being bilingual or multilingual are primarily that (1) it apparently delays language acquisition; (2) it aggravates language difficulties in children with language problems; (3) it may affect language skills such as verbal fluency, phonological ability, and grammar; and (4) it may decrease vocabulary in acquired languages [4]. It is also important to note that factors such as the age of acquisition of the second or third language and the frequency of use or exposure to these languages also influence the learning and maintenance of proficiency in the other languages [15].

Learning or improving a different language can be a challenging task. Thus, different tools and/or methods are continually being developed with the aim of facilitating or fostering the learning process [23,31,85]. This is the case of non-invasive transcranial electrical stimulation (tES) techniques.

Transcranial electrical stimulation techniques allow neural processes to be modulated in a non-invasive and safe way, both in people with a healthy brain and in those with neurological or neuropsychiatric disorders [66]. There are different types of tES methods: transcranial direct current stimulation (tDCS), transcranial random noise stimulation (tRNS), and transcranial alternating current stimulation (tACS). The main difference between them is the way that the weak electrical current is delivered to the scalp [62]. tDCS modulates neuronal activity by using a weak direct current (usually between 1 and 2 mA) which induces lengthy functional after-effects in the brain [58,86]. tRNS modulates neural activity by applying a low-intensity current with randomized

* Correspondence to: Department of Psychology, Faculty of Health Sciences, University of Deusto, Av. de las Universidades, 24, Bilbao 48007, Spain.
E-mail address: javier.pena@deusto.es (J. Peña).

https://doi.org/10.1016/j.bbr.2022.114165
Received 13 April 2022; Received in revised form 12 September 2022; Accepted 15 October 2022
Available online 18 October 2022

current intensity and frequency, while tACS allows intrinsic cortical oscillations to be manipulated with externally applied electrical frequencies [2,62,78].

In recent years, several studies have investigated the effects of tES on language among non-clinical samples (healthy population) [44]. Many of them have demonstrated positive effects on the improvement of different language abilities [48], such as naming [25,76]; verbal fluency [14,13,56]; and vocabulary [29,37]. However, according to recent scientific literature [6], not many studies have focused on the effects of these techniques on foreign language learning processes.

Specifically, tDCS has been frequently applied in different native language (L1) improvement studies. This can be seen in a meta-analysis conducted by Klaus and Schutter [44], who reviewed studies that used non-invasive brain stimulation techniques (transcranial magnetic stimulation, TMS; and tES) for improving first language production (e.g., picture naming, verbal fluency, semantic blocking) in healthy participants. From the 45 effect sizes included in their article, more than half (57.77%) used tDCS, while the rest used TMS. They observed small but reliable overall effects of the stimulation, with the TMS studies showing a higher significant effect (g =.22) compared to the tDCS studies (g =.38) [44]. Furthermore, recent studies have also used tDCS in healthy participants for enhancing language skills. Fiori et al. [26] analyzed verb-learning processes applying tDCS on healthy volunteers and using neuroimaging simultaneously. They found behavioral improvements with anodal tDCS and observed a significant decrease in task-related activity in the left inferior frontal gyrus (IFG) and its right counterpart [26]. Perceval et al. [64] applied tDCS on young and older adults in a randomized double-blind study, in which they observed positive effects on verbal learning and memory after multiple stimulation sessions [64]. Also, Owusu and Burianová [60] applied tDCS on healthy adults to study new word recall improvement, and obtained significant positive effects compared to the sham (placebo) group [60]. As far as the authors are aware, few studies have used other tES techniques to foster language acquisition in healthy participants. For example, Pasqualotto et al. [61] used tRNS in frontal and temporal regions for foreign language (FL) vocabulary learning (specifically, in the Swahili language). They observed that the stimulation on the posterior parietal area had positive long-term effects [61]. In another study conducted by Antonenko et al. [3], improvements in implicit learning after applying tACS were observed, especially in a group of older adults.

Certain montages tend to be repeatedly used in language studies. The most common ones are those that place the electrodes bilaterally, with the anodal current electrode being located over the left hemisphere frontotemporo-parietal areas (e.g., Wernicke's area, Broca's area, dorsolateral prefrontal cortex (DLPFC), etc.) [71]. The cathode electrode is usually placed over the brain areas of interest in the right hemisphere (e.g., right supraorbital area, right orbitofrontal cortex, etc.) [71]. The main argument for bilateral montage, according to different authors, is based on current knowledge about the strong association of different language functions (e.g., comprehension, production, verbal fluency, etc.) with different brain areas. Another well-founded reason for the high frequency of use of bilateral set-ups may be due to the data obtained by the commonly used measure of dichotic listening (DL), which allows the assessment of language lateralisation and auditory attention [38,5]. Several studies have found a significant association of DL with different language skills, such as language comprehension [5] or speech perception [36,80]. Among the observations of the results made in the DL studies, the phenomenon of the Right Ear Advantage (REA) stands out. The Right Ear Advantage occurs when, during the speech stimulus of the DL paradigm, participants tend to hit more of the stimuli presented in the right ear. One of the most widespread explanations for the REA is that it occurs due to the specialization of language processing in the left hemisphere and contralateral dominance of the auditory pathways [41,42,77]. In this regard, different tES studies that aimed to modify REA, found significant effects when using a bilateral set-up, but no effects when applying a unilateral montage [19,67].

Despite this, in recent years, Klaus and Schutter [43] suggested a completely new approach to noninvasive brain stimulation studies on language enhancement. They studied conventional montages (IFG, and posterior superior frontal gyrus, pSTG, with the reference electrode over the right supraorbital region), and proposed alternative electrode setups (IFG and pSTG with the reference electrode also on the left hemisphere), which could improve the focus on the brain area of interest for tDCS and provide more unequivocal results [43]. Different studies that have investigated the electric fields emitted by tDCS have observed that depending on where the electrode is placed (and with what intensity, it can affect the brain area under study to a lesser or greater extent [46,68]. Moreover, it seems that in the bilateral set-up, the maximum effect of the electric field emitted by the electrode is diffused to other areas [68]. Furthermore, depending on the area stimulated and the targets, a bilateral or unilateral montage may cause different effects [72]. However, since then, few studies have used different setups in language studies [27] beyond the conventional bilateral setup described above.

The main objective of this study was to investigate the effectiveness of different tES techniques on healthy participants for improving foreign vocabulary learning. Following Klaus and Schutter's suggestion, we applied three different types of tES (tDCS, tRNS and a combination of tDCS and tRNS) using a unilateral electrode montage over the left hemisphere (IFG and superior temporal gyrus, STG; area of stimulation influence over Wernicke's region) while participants were learning new foreign language vocabulary. This took place both during and immediately after the stimulation in a single session. Additionally, a two-week follow-up was conducted to assess the long-term effects of a single stimulation session on learning. We included a control-placebo group (sham condition).

Based on previous studies using tES to enhance language learning [61,73], we expected to find that tES would improve foreign vocabulary learning when compared to sham stimulation. Additionally, we expected that active tES stimulation would lead better performance than sham at the follow-up assessment. It was also our expectation that years of education could influence their overall performance when receiving tES, since different studies [16,30,8,10] have pointed out the influence of educational level on cognitive function (e.g., working memory).

2. Materials and methods

2.1. Participants

Sixty-four volunteers (49 females and 15 males, mean age 28.50 ± 10.76) participated in the study. The participants were divided into four groups, with 16 participants per group. All of them were adults and native Spanish speakers (L1) from the Basque Country, Spain. None of them reported any psychiatric or neurological disorders and they were right-handed according to the Edinburgh Handedness Inventory (tDCS group: 12.25 ± 2.60; tRNS group: 16.00 ± 9.28; tDCS-tRNS group: 14.00 ± 7.44; sham group: 13.56 ± 3.16) [59]. The majority of the participants were university students (42.2%were undergraduates or had completed a university degree; 23.4% were postgraduate students or had completed a postgraduate degree), of whom 9.4% had completed their PhD or were doctoral students, and 25.1% had completed a Certificate of Higher Education. Out of the total number of participants, 89.1% had Basque (the co-official language in the Basque Country) as their second language (L2), with a mean age of 1.98 (SD =.68) years of acquisition and different levels of proficiency (low, medium or high) compared to L1. All participants confirmed that they had been exposed to the English language at school at 7 years of age. They all had either normal or corrected-to-normal vision.

Exclusion criteria included: (1) suffering from frequent or severe headaches or migraines; (2) a history of brain surgery; (3) being pregnant; (4) a history of neurological disorder or injury (brain stroke, severe brain injury, epilepsy or convulsive seizures), and (5) having a metal brain implant.

The study was approved by the Ethics Committee of the University of Deusto (Ref: ETK-40/18–19) and was conducted in accordance with the ethical principles for medical research involving human subjects of the Declaration of Helsinki [87]. Participants did not receive any monetary compensation for taking part in the study.

2.2. Stimulus selection

2.2.1. Vocabulary

We selected 110 words, fifty-five in Spanish and their equivalent in English. The words were retrieved from the study by Moreno-Martinez and Montoro (2012). In their article, they proposed an ecological alternative to Snodgrass & Vanderwart [74], and provided 360 words with their corresponding color images for experimental and clinical use. They analyzed seven relevant psycholinguistic variables for each word (age of acquisition, familiarity, manipulability, name agreement, typicality, visual complexity and lexical frequency). The words used in the present study belonged to 17 different semantic categories (*see* Supplementary material, Table S1), and were selected according to frequency of use by native Spanish speakers: high frequency (common use, considered easy), medium frequency (considered moderately difficult), and low frequency (considered difficult) [57]. Therefore, from the fifty-five words of the paradigm, three had high frequency (5.45%), twenty-nine had medium frequency (52.72%), and twenty-three could be classified as having low frequency (41.81%). Fifty-five other words were added for the recognition part of the paradigm. These words were selected randomly from other nonstandardized sources.

2.2.2. Object pictures

Fifty-five pictures were selected from the 360 images in the article by Moreno-Martinez and Montoro (2012), which were paired with the previously chosen vocabulary. They were all high-quality color images ad (size: 615 ×458 pixels).

2.3. Experimental learning paradigm

The stimuli were presented using the SuperLab software (4.5 version), which also recorded participants responses. The learning paradigm used was based on the learning paradigm created and applied by Meinzer et al. (2014). This paradigm was divided into three parts: (1) learning phase, (2) recall phase and (3) recognition phase. During the learning or acquisition phase, words and images were presented simultaneously, first in Spanish (picture + Spanish word) for four seconds and then the same word and image in English (picture + English word) for another four seconds. In addition, when the English word appeared, the participant heard a recording of the word's correct pronunciation and were asked to repeat it. For each word (first shown in Spanish and then in English), two questions were employed to assess the participant's level of knowledge about the selected terms in English (Spanish word (4 s) → questions (4 s) → English word translation (4 s) + sound of the word). The questions were: "*Do you know the English word? Y/N*"; "*Do you remember the English word? Y/N*" (written originally in Spanish). The participants were instructed to answer honestly whether they knew that particular word in English (i.e., whether it was within the vocabulary previously learned in English), and if so, whether they could say it out loud, or on the contrary, despite knowing it, could not say it to the evaluator at that very moment (tip-of-the-tongue phenomenon, TOT) [1]. In the recall phase, the pictures were presented on their own, with a blank space below where the participant had to write the words learned in the previous phase correctly in English. The participant had ten seconds to type each word. Grammatically correct words were considered correct, regardless of whether they were written in upper or lower case. Finally, in the third phase, the pictures appeared with two words in English simultaneously, and participants had to choose the correct one by clicking the left or right mouse button. They had five seconds to choose the correct answer. All the responses were randomised each time a participant carried out the task. An example of each phase of the paradigm is shown in Fig. 1.

2.4. Measures

2.4.1. Adverse effects questionnaire

At the end of the first evaluation, participants completed a questionnaire to assess any perceived side effects, which consisted of 12 items (including headache, sore throat, scalp pain, skin tingling, skin itching, skin burning sensation, redness of the skin, numbness, dizziness, concentration problems, mood change and phosphenes).

2.4.2. The Edinburgh Handedness Inventory

Handedness was evaluated by the Edinburgh Handedness Inventory [59]. Participants were asked to indicate their preference of hand use for 10 everyday activities. Scores ranged from 100 (perfectly right-handed) to − 100 (perfectly left-handed).

2.5. Electrical stimulation protocol

Stimulation was administered using a light battery-driven current stimulator device (Neuroelectrics Inc., Barcelona) attached to the back of a neoprene cap. The electrical current was delivered for 20 min, with additional 30 s ramp-up and ramp-down phases. In the sham condition, current was applied using a 30 s ramp-up followed 20 min after by a 30 s ramp-down of activity. Electrode impedance was assessed before and during the stimulation application to ensure that it was under 10 kΩ. Electrodes were placed following the International 10–20 System [81]. The stimulated electric field for each electrode placement can be seen in Fig. 2.

2.5.1. Transcranial direct current stimulation (tDCS)

In the tDCS stimulation group, the anode was placed over the IFG region (equivalent to FC5 in the International Electrode Placement System 10/20) and the cathode was placed over the STG region (P5 according to the EEG 10/20). The participants received 1.5 mA via two saline-soaked (5 ml approximately per sponge), 8 cm^2 circular sponges.

2.5.2. Transcranial random noise stimulation (tRNS)

In the tRNS group the electrodes were placed over the same areas (P5 and FC5), with 1.5 mA current (100–500 Hz). It was applied via two saline-soaked (5 ml approximately per sponge), 8 cm2 circular sponges.

2.5.3. Combined tDCS-tRNS stimulation

In this type of stimulation 1 mA tDCS with 0.5 mA of tRNS (high-frequency: 100–500 Hz) was applied simultaneously and stimulation setup was the same as in the other sessions.

2.5.4. Sham/placebo condition

Despite not receiving real stimulation, as the study design was double blind, the same electrode placement was used as in the other groups, with circular saline-soaked sponges. Therefore, the current was applied using a 30-s ramp-up at the beginning, and 20 min later a 30-s ramp-down of activity.

2.6. Procedure

The study had a randomized, sham-controlled, parallel group, double-blind design. The volunteers were randomly allocated to the different condition groups (either tDCS, tRNS, tDCS/tRNS or sham) using Research Randomizer online software [82].

All participants were tested individually in two different sessions. In the single-session (first session), subjects had to complete the three phases of the experimental vocabulary-learning paradigm. They were seated in front of a tablet screen in a quiet room, and they received either active or sham stimulation during the learning phase for 20 min, to

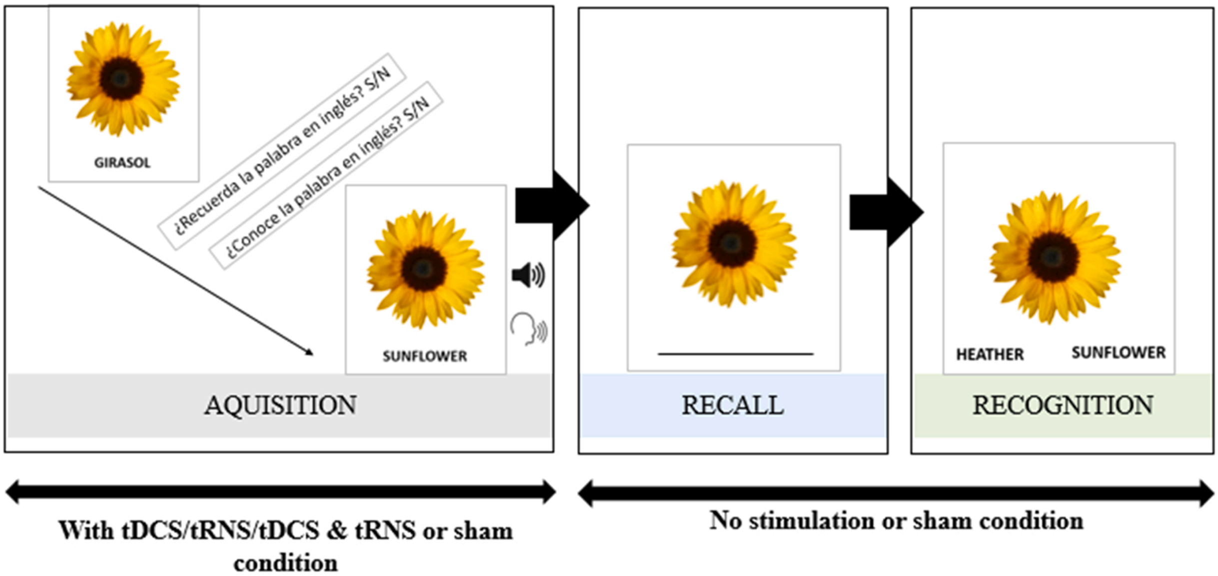

Fig. 1. An example of each phase of the foreign vocabulary-learning paradigm. Note: The participants completed the three phases in the first session; but the last two phases (recall and recognition) were implemented two weeks later, with no stimulation.

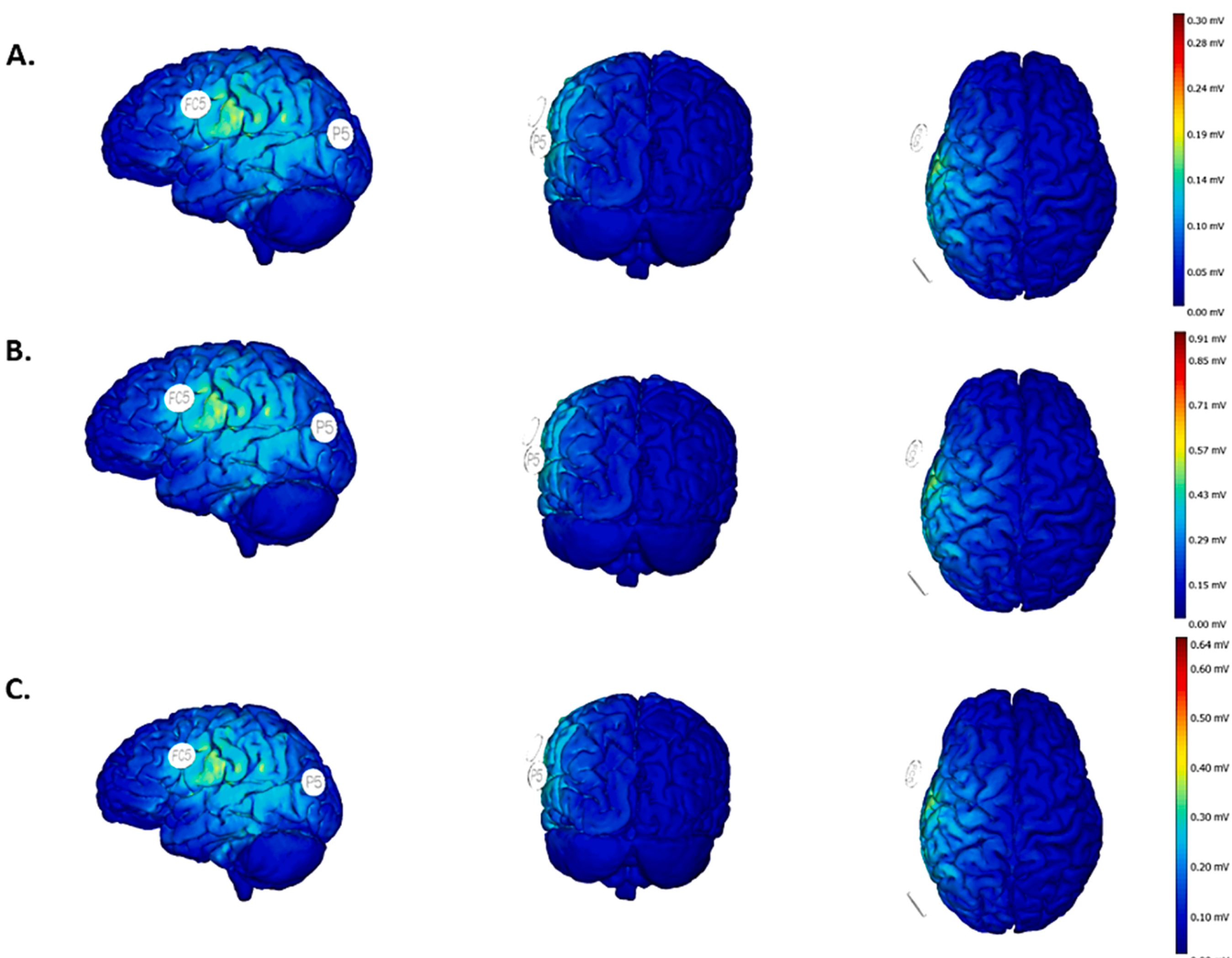

Fig. 2. Electrode placement for stimulation (tDCS, tRNS, combined tDCS-tRNS stimulation). Note: Electrode montage influence map provided by the Stim Weaver software (Neuroelectrics Inc., Barcelona) based on a realistic head model [55]. A.: tDCS; B.: tRNS; C.: combined tDCS-tRNS.

maximize stimulation effects [73]. The stimulation cap was then removed, and they performed the recall and recognition phases without receiving any stimulation (offline).

In the second session, about two weeks later (14.67 ± 1.61 days, range 9 [min 11, max 19 days]), the participants performed the recall and recognition tasks of the vocabulary-learning paradigm, without stimulation. Two of the 64 participants were not able to attend the follow-up assessment because they contracted the COVID-19 virus. Therefore, 64 participants were assessed in a single stimulation session, but only 62 were present at the follow-up session. Thus, in the second session the groups remained with the same sample (N = 16), with the exception of the tRNS group, which was left with a sample of 14 participants. Fig. 3.

3. Statistical analysis

The statistical analyses were carried out using SPSS version 27 for Windows (IBM [18]). The normality of the data was assessed using the Kolmogorov-Smirnov test. Descriptive analyses were performed to show the baseline characteristics of the participants in more detail. Analysis of variance (ANOVA) and chi-squared tests ($\chi 2$) were also used to analyze between-group differences by age, years of education, handedness, number of sleep hours, and stimulants consumed (e.g., coffee, tea, energy drinks, etc.).

Analyses of covariance (ANCOVA) were performed, with the single-session (offline outcome) stimulation scores for recall, and follow-up session scores as dependent variables (for offline and follow-up stimulation effects comparison, recall phase scores were used), and the baseline English language knowledge scores as a covariate (baseline knowledge of the English vocabulary).

Finally, moderation analyses were conducted using PROCESS macro (V4.0) for SPSS [33], in order to test whether years of education could influence the relationship between the effects of stimulation and learning performance. The significance level was set at 0.05. The Bonferroni method was used for correction of multiple comparisons.

Partial eta-squared (η_p^2) was used to measure effect size in ANCOVA. For the intervals of interpretation of η_p^2, 0.01 was considered a small effect size, 0.06 was considered a medium effect size, and 0.14 was considered a large effect size [17].

4. Results

4.1. Sociodemographic characteristics of the groups

Baseline variables of the groups are shown in Table 1. No significant differences were found among the groups in terms of age, sex, years of education, and handedness (Edinburgh Handedness Inventory). Before the assessment, participants were also asked whether they had slept fewer or more hours than usual, or whether they had drunk fewer or more stimulant beverages than usual. No statistically significant differences were found between groups in the consumption of stimulant drinks (e.g., tea, coffee, energy drinks) or number of sleep hours before the evaluation.

4.2. Overall effects of tES on foreign vocabulary learning

All the results obtained by the participants are displayed in Table 2. In the offline session, there were no statistically significant differences in learning between the experimental conditions ($F_{(3,\ 59)} = 1.33$; $p = .27$; $\eta_p^2 = .06$).

In the follow-up session, two weeks later, there were significant differences between the four groups ($F_{(3,\ 57)} = 3.10$; $p = .034$; $\eta_p^2 = .14$). *Post hoc* analyses indicated that after two weeks, the tRNS group remembered more words (*M*= 18.59, *SE*= 1.74) compared to the sham group (*M* = 11.68; *SE* = 1.67). However, no statistically significant differences were found between tDCS or tDCS/tRNS and sham.

4.3. Effects of other variables on learning performance

We analyzed whether years of education could influence the language learning performance of the participants performing moderator analyses.

There was no statistically significant moderation of the years of education variable that could explain the relationship between condition received and language learning achievement ($\beta = -.47$ [−2.31 to 1.36], *SE*=.92, $t = -.52$, $p = .60$).

4.4. Adverse effects

Participants did not report any serious discomfort or unusual sensations in their scalp. None of the volunteers reported experiencing severe or significant adverse effects. Likewise, no statistically significant differences were observed between the groups in terms of adverse effects (see Table 3). In general, participants reported not being able to distinguish whether they had received active or sham stimulation.

5. Discussion

This study aimed to compare and test the effect that different tES techniques have on improving foreign vocabulary learning in healthy adults. The overall results showed benefits of tES in learning two weeks later, notably enhancing the recall of the new foreign words learned by the participants who had received tRNS. No immediate differences were observed in the learning performance of the participants immediately after the stimulation (first experimental session). Finally, there was no evidence that years of education moderated the effects of stimulation on learning performance. Overall, these results suggest possible long-term benefits of tES (in particular, tRNS) on the processes involved in foreign language learning by healthy individuals.

Despite finding positive effects of the stimulation two weeks later, no significant differences were observed between the active and sham stimulation groups in the first experimental session. The results reported

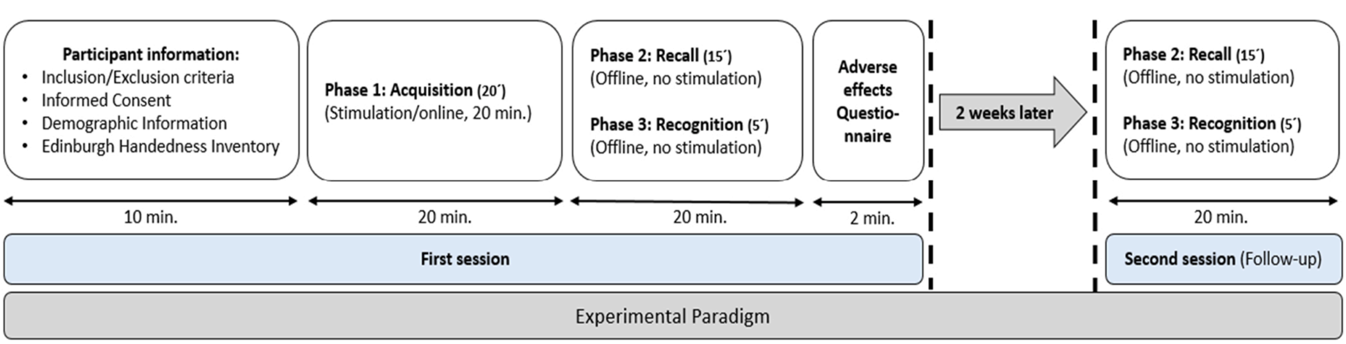

Fig. 3. *Procedure.*

Table 1
Baseline demographic characteristics of participants according to the assigned group condition.

	tDCS group (n = 16)	tRNS group (n = 16)	tDCS-tRNS group (n = 16)	Sham group (n = 16)		
	M (SD)	M (SD)	M (SD)	M (SD)	Statistic	*p*
Age	28.00(10.11)	32.25(13.54)	25.68 (7.31)	28.06 (11.12)	*F*= 1.03	.38
Years of education	15.81(3.06)	17.06 (3.02)	16.25 (2.64)	16.62 (1.96)	*F*= .62	.60
Sex: n (%)					X^2 =.96	.81
Female	12 (75)	13 (81.25)	11 (68.75)	13 (81.25)		
Male	4 (25)	3 (18.75)	5 (31.25)	3 (18.75)		
Edinburgh Handedness	12.25(2.60)	16.00(9.28)	14.00(7.44)	13.56(3.16)	*F*= .97	.41
Number of slept hours	6.77(1.18)	6.95(0.68)	7.34(1.18)	6.96(1.26)	*F*= 1.07	.37
Number of stimulants	0.81 (1.16)	0.96(1.19)	0.69(0.87)	0.81(0.98)	*F*= .20	.90

Note. SD = Standard Deviation.

Table 2
Differences in the number of correct English words (marginal means) remembered and learned by the participants in the single-session (offline outcome) and at follow-up (two weeks later). And results of pairwise comparisons of all the groups on the follow-up.

	tDCS		tRNS		tRNS-tDCS		Sham		ANCOVA						
	M	SE	M	SE	M	SE	M	SE	df	F	p	η^2_p	Comparison group		Post hocp-value
Single session	18.66	1.87	19.44	1.87	15.06	1.86	15.69	1.89	3	1.33	.27	.06	Placebo	tDCS	.28
														tRNS	.20
														tDCS & tRNS	.83
													tDCS	tRNS	.75
														tDCS & tRNS	.14
													tRNS	tDCS & tRNS	.95
Follow-up	16.70	1.67	18.59	1.74	13.95	1.73	11.74	1.70	3	3.09	.034 *	.14	Placebo	tDCS	.23
														tRNS	.037 *
														tDCS & tRNS	1.00
													tDCS	tRNS	1.00
														tDCS & tRNS	1.00
													tRNS	tDCS & tRNS	.39

Note: M= Mean; *SE* = Standard Error; *tDCS* = transcranial direct current stimulation; *tRNS*= transcranial random noise stimulation; *tRNS-tDCS*= Combined tDCS-tRNS stimulation; *Sham*=placebo condition*; ANCOVA*= Analyses of covariance, *M* = mean; *SE* = Standard Error; *df* = degrees of freedom;* $p < 0.05$, LL = lower limit; UL= upper limit.

Table 3
Side effects experienced and reported by participants from active and sham stimulation groups.

Adverse effects	tDCS N (%)	tRNS N (%)	tDCS-tRNS stimulation N (%)	Placebo N (%)	X^2	*p*
Headache	2 (12.50)	4 (25)	2 (12.50)	1 (6.25)	2.37	.50
Throat sore	0 (0)	0 (0)	1 (6.25)	0 (0)	3.05	.40
Scalp pain	0 (0)	2 (12.50)	0 (0)	0 (0)	6.19	.10
Skin tingling	5 (31.25)	8 (50)	4 (25)	5 (31.25)	7.76	.61
Skin itching	6 (37.50)	8 (50)	3 (18.75)	4 (25)	5.39	.36
Skin burning sensation	1 (6.25)	2 (12.50)	0 (0)	1 (6.25)	3.95	.68
Redness of the skin	0 (0)	1 (6.25)	0 (0)	0 (0)	3.05	.40
Numbness	1 (6.25)	2 (12.50)	0 (0)	2 (12.50)	5.54	.43
Concentration problems	1 (6.25)	2 (12.50)	3 (18.75)	2 (12.50)	2.69	.67
Mood change	0 (0)	1 (6.25)	0 (0)	1 (6.25)	2.02	.58
Phosphenes	0 (0)	1 (6.25)	0 (0)	1 (6.25)	2.02	.58

in this study contrast with results obtained by other similar studies that applied a tDCS bilateral setup, with the anode over Wernicke's area and the cathodal electrode over the contralateral supraorbital region or right frontopolar cortex, for 20 or 24 min with an intensity of 1 mA or 1.5 mA [28,26,29,60]. They employed nonword learning tasks [28,29,60], and verbs in a foreign language [26]. Another study obtained the same immediate positive results in a single session by applying bilateral tACS (6 Hz) on the same brain areas mentioned above, with an intensity of 1 mA [3]. Nevertheless, while scientific evidence was found of the immediate beneficial effects of stimulation (especially tDCS) [28,26,29,3,60,73], other similar studies can also be found that observed no beneficial effects of stimulation in a single experimental session [21,27,61,63,84,83], and therefore, were in line with this study's results. These studies applied a bilateral montage with anodal tDCS over the left hemisphere, specifically over Broca's [21] or Wernicke's area [27,63] for 20 min with an intensity of 1 mA [21,63], or 2 mA [27]. They used artificial grammar [21], foreign vocabulary [61,63] and nonword learning tasks [27].

The variability of the results among the different studies may be due to several factors. This issue has been studied by several authors who reported the lack of standardized stimulation protocols (e.g. online vs. offline stimulation, electrode placement, current intensity, etc.) [22,54], small study samples commonly used [53,54], different experiment conditions or sample characteristics (e.g., healthy participants) [35,34], among others. In our case, this lack of "immediate" improvement of tES in learning new FL words may be due to the characteristics either of the experiment itself, or to the participant variables (e.g., level of fatigue, ability to concentrate, time of evaluation, ability to learn, different levels of proficiency in L2 and L3, etc.). Regarding the protocol characteristics, a major influencing factor could be the electrode setup employed in the study. Our results are based on a unihemispheric setup, specifically on the proposal previously made by Klaus and Schutter [43]. As it is a less common setup used for language learning studies, comparison of its effects could be complicated, since the most widespread and frequently used is the bilateral setup applied with tDCS. Likewise, previous authors have indicated the influence of a wide range of other factors on the results of stimulation, from the recruitment process to the biological characteristics of the participants [79]. These factors may also have affected the results obtained in the present study.

Regarding the sample, it should be highlighted that participants came from a multilingual environment. In the Basque Country there are two official languages (Basque and Spanish), and people are taught a third language from childhood (from the age of seven, basic English is taught at schools). In addition, from the age of 12, some high schools offer students the option of learning a fourth language, usually French or German. Therefore, the participants were familiar with language learning, despite having different levels of proficiency in L2 and L3 (unbalanced bilinguals), which can either favor or interfere with the immediate benefits of stimulation when it comes to improving foreign language learning [39,45,49,65,7,88]. In addition, the target population is a healthy sample. This may cause the immediate beneficial effects of a single stimulation session to be less noticeable as they might be in clinical samples, specifically those in which the baseline for certain cognitive abilities is usually lower than the average baseline (ceiling effect) [34].

To meet one of the further aims of the present study, a follow-up assessment was carried out two weeks later. It was observed that the participants who had previously received stimulation performed significantly better compared to the sham stimulation group. Specifically, it was found that only those individuals who received tRNS obtained significantly better results than the other participants. All participants remembered fewer words, but those who received tDCS, tRNS or tDCS/tRNS, especially tRNS, were able to retain more foreign words in the long term. These results are consistent with the observations made by previous studies. For example, in a study conducted by Pasqualotto and colleagues (2015), they applied bilateral high-frequency (100–500 Hz) tRNS in healthy adults (monolingual, with no previous exposure to the target language) over the DLPFC and posterior parietal cortex (separately) for 20 min with the aim of investigating its effects on foreign vocabulary learning (English-Swahili). They found no differences between groups in overall learning; however, one week later, at follow-up; they observed improvement in those who had received stimulation, which highlighted the role of the DLPFC in language learning processes [61]. Also, in a recently published study in which they applied bilateral tDCS for 20 min with an intensity of 1–1.5 mA over the DLPFC in healthy adults for foreign language learning while using mental imagery [11], the beneficial effects of stimulation were observed after one week, at the follow-up assessment. Therefore, their findings also suggest a long-term effect of anodal tDCS stimulation over the DLPFC (F3 according to the international 10–20 system).

The long-term effects observed as a result of a single stimulation session may be due to several reasons. One of them may be associated with the mechanism of how tRNS works on neuronal activity [20,2,78]. Although the function of tRNS is not entirely clear, evidence from several studies has suggested that the tRNS mechanism seems to have more gradual beneficial effects over time, which are not observed immediately (as is more often the case with tDCS), but in the long term [20,69,75]. It may also be due to the effect of tES on the consolidation processes of new information. Stimulation could facilitate the consolidation of new information over time or ease neuronal reactivation during sleep [11,61,62,70,75]. Another possibility may be the applied foreign vocabulary-learning task in this study. As in other similar studies, the paradigm employed is based on learning by association (in this case, word-picture association), a widely used and effective language learning technique [52]. According to scientific literature, the combination of an appropriate training task and an adequate stimulation protocol may be key to enhancing the target cognitive ability [75].

Finally, in this study investigated whether years of education could influence the effects of stimulation and task performance, as it is considered a relevant variable in learning processes [24,40,47]. However, it was not found to influence the learning performance of the participants. These results are not consistent with previous similar studies. Berryhill & Jones [8] conducted a study in which tDCS was applied on the prefrontal cortex of a sample of healthy older adults to improve working memory; they observed that the stimulation benefits were greater in those older adults with higher levels of education. However, the characteristics of the sample could be one of the main reasons why years of education did not seem to have had an effect on the results in our study. The participants were mostly young adults with high education levels, resulting in a very homogeneous sample concerning educational level. This could potentially limit the influence of the variable reported by other studies.

5.1. Limitations and future directions

There are a number of limitations in this study that need to be considered when interpreting the results obtained. Firstly, despite having used a similar sample size to other related studies, we believe that it would have been preferable to increase the number of participants per group due to the number of comparison groups. Secondly, the comparison design in the present study was between subjects. Although this is an appropriate design for the investigation of the hypotheses proposed here, within-subjects analyses should also be carried out in future similar studies in order to obtain more information on the effect of tES. Thirdly, due to time constraints, it was not possible to carry out an extensive assessment of the basic foreign language level of each participant or evaluate their learning styles. It is true that the paradigm itself incorporates a brief foreign language vocabulary assessment of each participant's baseline level. However, it would have been interesting to obtain more detailed information and thus analyze whether the effects of the stimulation might have been more noticeable depending on language proficiency (e.g., the lower the proficiency level in L3, the greater the sensitivity of the individual to the effects of tES). Therefore, we propose that future studies should make an additional extended assessment of the baseline level of the foreign language of each participant. Such data could provide additional details or possible explanations for the results obtained in this study, in addition to the extent of the enhancing effects of tES.

6. Conclusions

In summary, the study described here has contributed some new, relevant data to the existing evidence on the beneficial effects of tES on foreign language learning processes. It suggests that noninvasive brain stimulation could be a useful tool to enhance the healthy brain and learn more about it. It is also an accessible instrument that can be easily applied to scenarios other than research. However, the scarcity of studies on the subject and the heterogeneity of stimulation protocols indicates that there is still a long way to go until robust scientific evidence on this particular topic can be provided. This study has shown that tRNS can reinforce foreign language learning in the long term, fostering the recall of new words previously learned with the help of stimulation. Furthermore, this study reinforces the idea that it would be interesting to encourage the use of other types of tES and other types of setups, in addition to tDCS and bilateral electrode placement. However, we are aware that numerous issues (e.g., methodology, stimulation protocols, etc.) need to be addressed before normalizing the use of such tools in other contexts outside the research setting, such as academic contexts.

Funding

This work was supported by the Jesus de Gangoiti Barrera Foundation; the Department of Education of the Basque Country Government [T946–16]; and a Research Staff Training Programme Grant from the University of Deusto (Bilbao, Spain).

CRediT authorship contribution statement

Yolanda Balboa-Bandeira: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Leire Zubiaurre-Elorza:** Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing. **M. Acebo Garcia-Guerrero:** Resources, Supervision, Writing – review & editing. **Naroa Ibarretxe-Bilbao:** Supervision, Writing – review & editing. **Natalia Ojeda:** Supervision, Writing – review & editing. **Javier Peña:** Conceptualization, Methodology, Software, Verification, Resources, Supervision, Writing – review & editing.

Conflict of Interest Statement

The authors declare that are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome.

Data Availability

Data will be made available on request.

Acknowledgments

The authors would like to thank all the participants involved in the study, as well as Julian Thomas and Susana Quintas of the English Editing Service.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bbr.2022.114165.

References

[1] L. Abrams, D.K. Davis, The tip-of-the-tongue phenomenon. Cognition, Language and Aging, John Benjamins Publishing Company, 2016, pp. 13–53, https://doi.org/10.1075/z.200.
[2] A. Antal, C.S. Herrmann, Transcranial alternating current and random noise stimulation: possible mechanisms, Neural Plast. 2016 (2016) 1–12, https://doi.org/10.1155/2016/3616807.
[3] D. Antonenko, M. Faxel, U. Grittner, M. Lavidor, A. Floël, Effects of transcranial alternating current stimulation on cognitive functions in healthy young and older adults, Neural Plast. (2016) *2016*, https://doi.org/10.1155/2016/4274127.
[4] A. Ardila, Ventajas y desventajas del bilingüismo, Forma Y. Func. 25 (2012) 99–114.
[5] A.E. Asbjørnsen, T. Helland, Dichotic listening performance predicts language comprehension, Laterality 11 (3) (2006) 251–262, https://doi.org/10.1080/13576500500489360.
[6] Y. Balboa-Bandeira, L. Zubiaurre-Elorza, N. Ibarretxe-Bilbao, N. Ojeda, J. Peña, Effect of transcranial electrical stimulation techniques on second and foreign language learning enhancement in healthy adults: a systematic review and meta-analysis, Neuropsychologia (2021) 1–37.
[7] J. Bartolotti, V. Marian, Language learning and control in monolinguals and bilinguals, Cogn. Sci. 36 (6) (2012) 1129–1147, https://doi.org/10.1111/j.1551-6709.2012.01243.x.
[8] M.E. Berryhill, K.T. Jones, tDCS selectively improves working memory in older adults with more education, Neurosci. Lett. 521 (2) (2012) 148–151, https://doi.org/10.1016/j.neulet.2012.05.074.
[9] E. Bialystok, F.I.M. Craik, G. Luk, Bilingualism: consequences for mind and brain. Trends in Cognitive Sciences 16 (4) (2012) 240–250, https://doi.org/10.1016/j.tics.2012.03.001.
[10] B. Boller, S. Mellah, G. Ducharme-Laliberté, S. Belleville, Relationships between years of education, regional grey matter volumes, and working memory-related brain activity in healthy older adults, Brain Imaging Behav. 11 (2) (2017) 304–317, https://doi.org/10.1007/s11682-016-9621-7.
[11] A.J. Bolling, V.L. King, T. Enam, I.M. McDonough, Using transcranial direct current stimulation (tDCS) on the dorsolateral prefrontal cortex to promote long-term foreign language vocabulary learning, Brain Cogn. 154 (September) (2021), https://doi.org/10.1016/j.bandc.2021.105789.
[12] Breitenstein, C., Jansen, A., Deppe, M., Foerster, A. F., Sommer, J., Wolbers, T., & Knecht, S. (2005). Hippocampus activity differentiates good from poor learners of a novel lexicon. NeuroImage, 25(3), 958–968. https://doi.org/10.1016/j.neuroimage.2004.12.019.
[13] Z. Cattaneo, A. Pisoni, C. Papagno, Transcranial direct current stimulation over Broca's region improves phonemic and semantic fluency in healthy individuals, Neuroscience 183 (2011) 64–70, https://doi.org/10.1016/j.neuroscience.2011.03.058.
[14] Z. Cattaneo, A. Pisoni, M. Gallucci, C. Papagno, TDCS effects on verbal fluency: a response to Vannorsdall et al. (2016), Cogn. Behav. Neurol. 29 (3) (2016) 117–121, https://doi.org/10.1097/WNN.0000000000000098.
[15] J. Cenoz, The acquisition of additional languages, Estud. De. Linguist. Ingl. Apl. (ELIA) 8 (2008) 219–224.
[16] Y. Chen, C. Lv, X. Li, J. Zhang, K. Chen, Z. Liu, H. Li, J. Fan, T. Qin, L. Luo, Z. Zhang, The positive impacts of early-life education on cognition, leisure activity, and brain structure in healthy aging, Aging 11 (14) (2019) 4923–4942, https://doi.org/10.18632/aging.102088.
[17] Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. Routledge Academic.
[18] I.B.M. Corp. (2020). IBM SPSS Statistics for Windows, Version 27.0 (No. 27). IBM Corp.
[19] A. D'Anselmo, G. Prete, L. Tommasi, A. Brancucci, The dichotic right ear advantage does not change with transcranial direct current stimulation (tDCS), Brain Stimul. 8 (6) (2015) 1238–1240, https://doi.org/10.1016/j.brs.2015.09.007.
[20] D. De Ridder, T. Stöckl, W.T. To, B. Langguth, S. Vanneste, Noninvasive transcranial magnetic and electrical stimulation: working mechanisms. Rhythmic Stimulation Procedures in Neuromodulation, Elsevier Inc, 2017, https://doi.org/10.1016/B978-0-12-803726-3.00007-9.
[21] M.H. De Vries, A.C.R. Barth, S. Maiworm, S. Knecht, P. Zwitserlood, A. Flöel, Electrical stimulation of Broca's area enhances implicit learning of an artificial grammar, J. Cogn. Neurosci. 22 (11) (2010) 2427–2436, https://doi.org/10.1162/jocn.2009.21385.
[22] J. Dedoncker, A.R. Brunoni, C. Baeken, M.A. Vanderhasselt, A systematic review and meta-analysis of the effects of transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex in healthy and neuropsychiatric samples: influence of stimulation parameters, Brain Stimul. 9 (4) (2016) 501–517, https://doi.org/10.1016/j.brs.2016.04.006.
[23] H. Dehghanzadeh, H. Dehghanzadeh, Investigating effects of digital gamification-based language learning: a systematic review, J. Engl. Lang. Teach. Learn. 12 (25) (2020) 54–93, https://doi.org/10.22034/ELT.2020.10676.
[24] S. Fernández-Cabello, C. Valls-Pedret, M. Schurz, D. Vidal-Piñeiro, R. Sala-Llonch, N. Bargallo, E. Ros, D. Bartrés-Faz, White matter hyperintensities and cognitive reserve during a working memory task: a functional magnetic resonance imaging study in cognitively normal older adults, Neurobiol. Aging 48 (2016) 23–33, https://doi.org/10.1016/j.neurobiolaging.2016.08.008.
[25] A. Fertonani, S. Rosini, M. Cotelli, P.M. Rossini, C. Miniussi, Naming facilitation induced by transcranial direct current stimulation, Behav. Brain Res. 208 (2) (2010) 311–318, https://doi.org/10.1016/j.bbr.2009.10.030.
[26] V. Fiori, L. Kunz, P. Kuhnke, P. Marangolo, G. Hartwigsen, Transcranial direct current stimulation (tDCS) facilitates verb learning by altering effective connectivity in the healthy brain, NeuroImage 181 (2018) 550–559, https://doi.org/10.1016/j.neuroimage.2018.07.040.
[27] V. Fiori, M. Nitsche, L. Iasevoli, G. Cucuzza, C. Caltagirone, P. Marangolo, Differential effects of bihemispheric and unihemispheric transcranial direct current stimulation in young and elderly adults in verbal learning, Behav. Brain Res. 321 (2017) 170–175, https://doi.org/10.1016/j.bbr.2016.12.044.
[28] V. Fiori, M. Coccia, C.V. Marinelli, V. Vecchi, S. Bonifazi, M. Gabriella Ceravolo, L. Provinciali, F. Tomaiuolo, P. Marangolo, Transcranial direct current stimulation improves word retrieval in healthy and nonfluent aphasic subjects, J. Cogn. Neurosci. 23 (9) (2011) 2309–2323, https://doi.org/10.1162/jocn.2010.21579.
[29] A. Flöel, N. Rösser, O. Michka, S. Knecht, C. Breitenstein, Noninvasive brain stimulation improves language learning, J. Cogn. Neurosci. 20 (8) (2008) 1415–1422, https://doi.org/10.1162/jocn.2008.20098.
[30] N. Fournet, J.L. Roulin, F. Vallet, M. Beaudoin, S. Agrigoroaei, A. Paignon, C. Dantzer, O. Desrichard, Evaluating short-term and working memory in older adults: French normative data, Aging Ment. Health 16 (7) (2012) 922–930, https://doi.org/10.1080/13607863.2012.674487.
[31] E.M. Golonka, A.R. Bowles, V.M. Frank, D.L. Richardson, S. Freynik, Technologies for foreign language learning: A review of technology types and their effectiveness, Comput. Assist. Lang. Learn. Vol. 27 (Issue 1) (2014) 70–105, https://doi.org/10.1080/09588221.2012.700315.
[32] Grin, F., Sfreddo, C., & Vaillancourt, F. (2010). The Economics of the Multilingual Workplace. Routledge.
[33] A.F. Hayes, Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-based Approach, second ed., The Guilford Press, 2018.
[34] J.C. Horvath, J.D. Forte, O. Carter, Quantitative review finds no evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS), Brain Stimul. 8 (3) (2015) 535–550, https://doi.org/10.1016/j.brs.2015.01.400.
[35] J.C. Horvath, J.D. Forte, O. Carter, Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: a systematic review, Neuropsychologia 66 (2015) 213–236, https://doi.org/10.1016/j.neuropsychologia.2014.11.021.
[36] K. Hugdahl, R. Westerhausen, Speech processing asymmetry revealed by dichotic listening and functional brain imaging, Neuropsychologia 93 (2016) 466–481, https://doi.org/10.1016/j.neuropsychologia.2015.12.011.
[37] E.K. Hussey, N. Ward, K. Christianson, A.F. Kramer, Language and memory improvements following tDCS of left lateral prefrontal cortex, PLoS ONE 10 (11) (2015) 1–31, https://doi.org/10.1371/journal.pone.0141417.

[38] L. Jäncke, H. Steinmetz, J. Volkmann, Dichotic listening: what does it measure? Neuropsychologia 30 (11) (1992) 941–950, https://doi.org/10.1016/0028-3932(92)90047-P.
[39] M. Kaushanskaya, V. Marian, Bilingualism reduces native-language interference during novel-word learning, J. Exp. Psychol.: Learn., Mem., Cogn. 35 (3) (2009) 829–835, https://doi.org/10.1037/a0015275.
[40] J. Kim, J. Chey, S. Kim, H. Kim, The effect of education on regional brain metabolism and its functional connectivity in an aged population utilizing positron emission tomography, Neurosci. Res. (2015), https://doi.org/10.1016/j.neures.2014.12.009.
[41] D. Kimura, Cerebral dominance and the perception of verbal stimuli, Can. J. Psychol. /Rev. Can. De. Psychol. 15 (3) (1961) 166–171, https://doi.org/10.1037/h0083219.
[42] D. Kimura, Functional asymmetry of the brain in dichotic listening, Cortex 3 (2) (1967) 163–178, https://doi.org/10.1016/s0010-9452(67)80010-8.
[43] J. Klaus, D.J.L.G. Schutter, Putting focus on transcranial direct current stimulation in language production studies, PLoS ONE 13 (8) (2018) 18–20, https://doi.org/10.1371/journal.pone.0202730.
[44] J. Klaus, D.J.L.G. Schutter, Non-invasive brain stimulation to investigate language production in healthy speakers: a meta-analysis, Brain Cogn. 123 (November 2017) (2018) 10–22, https://doi.org/10.1016/j.bandc.2018.02.007.
[45] J.F. Kroll, E. Stewart, Category interference in translation and picture naming: evidence for asymmetric connections between bilingual memory representations, J. Mem. Lang. 33 (2) (1994) 149–174, https://doi.org/10.1006/JMLA.1994.1008.
[46] I. Laakso, S. Tanaka, M. Mikkonen, S. Koyama, N. Sadato, A. Hirata, Electric fields of motor and frontal tDCS in a standard brain space: a computer simulation study, NeuroImage 137 (2016) 140–151, https://doi.org/10.1016/j.neuroimage.2016.05.032.
[47] Y. Liao, R. Liu, L. Teng, Y. Lee, Cognitive reserve: a SPECT study of 132 alzheimer ' s disease patients with an education range of 0 – 19 years, Dement. Geriatr. Cogn. Disord. 11217 (2005) 8–14, https://doi.org/10.1159/000085068.
[48] J. Livengood, J.J. van Steenburgh, R. Jayatillake, T.D. Vannorsdall, D.J. Schretlen, B. Gordon, Transcranial direct current stimulation and language, in: International Encyclopedia of the Social & Behavioral Sciences: Second Edition, Elsevier,, 2015, https://doi.org/10.1016/B978-0-08-097086-8.54052-5.
[49] J.T. Maluch, M. Neumann, S. Kempert, Bilingualism as a resource for foreign language learning of language minority students? Empirical evidence from a longitudinal study during primary and secondary school in Germany, Learn. Individ. Differ. 51 (2016) 111–118, https://doi.org/10.1016/j.lindif.2016.09.001.
[50] Marian, V., & Shook, A. (2012). The Cognitive Benefits of Being Bilingual. http://www.dana.org/news/cerebrum/detail.aspx?id=39638.
[51] J. Mårtensson, J. Eriksson, N.C. Bodammer, M. Lindgren, M. Johansson, L. Nyberg, M. Lövdén, Growth of language-related brain areas after foreign language learning, NeuroImage 63 (1) (2012) 240–244, https://doi.org/10.1016/j.neuroimage.2012.06.043.
[52] Meara, P. (2009). Connected Words (Vol. 24). John Benjamins Publishing Company. https://doi.org/10.1075/lllt.24.
[53] J. Medina, S. Cason, No evidential value in samples of transcranial direct current stimulation (tDCS) studies of cognition and working memory in healthy populations, Cortex 94 (2017) 131–141, https://doi.org/10.1016/j.cortex.2017.06.021.
[54] T. Minarik, B. Berger, L. Althaus, V. Bader, B. Biebl, F. Brotzeller, T. Fusban, J. Hegemann, L. Jesteadt, L. Kalweit, M. Leitner, F. Linke, N. Nabielska, T. Reiter, D. Schmitt, A. Spraetz, P. Sauseng, The importance of sample size for reproducibility of tDCS effects, Front. Hum. Neurosci. 10 (SEP2016) (2016) 1–5, https://doi.org/10.3389/fnhum.2016.00453.
[55] P.C. Miranda, A. Mekonnen, R. Salvador, G. Ruffini, The electric field in the cortex during transcranial current stimulation, NeuroImage 70 (2013) 48–58, https://doi.org/10.1016/j.neuroimage.2012.12.034.
[56] A. Monti, R. Ferrucci, M. Fumagalli, F. Mameli, F. Cogiamanian, G. Ardolino, A. Priori, Transcranial direct current stimulation (tDCS) and language, J. Neurol. Neurosurg. Psychiatry (2013) 832–842, https://doi.org/10.1136/jnnp-2012-302825.
[57] F.J. Moreno-Martínez, P.R. Montoro, An ecological alternative to Snodgrass & Vanderwart: 360 high quality colour images with norms for seven psycholinguistic variables, PLoS ONE 7 (5) (2012), https://doi.org/10.1371/journal.pone.0037527.
[58] M. Nitsche, W. Paulus, Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation, J. Physiol. 527 (3) (2000) 633–639, https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x.
[59] R.C. Oldfield, The assessment and analysis of handedness: the Edinburgh inventory, Neuropsychologia 9 (1) (1971) 97–113.
[60] B.A.K. Owusu, H. Burianová, Transcranial direct current stimulation improves novel word recall in healthy adults, J. Neurolinguist. 53 (August 2019) (2020) 1–9, https://doi.org/10.1016/j.jneuroling.2019.100862.
[61] A. Pasqualotto, B. Kobanbay, M.J. Proulx, Neural stimulation has a long-term effect on foreign vocabulary acquisition, Neural Plast. 2015 (2015) 1–7, https://doi.org/10.1155/2015/671705.
[62] W. Paulus, Transcranial electrical stimulation (tES - tDCS; tRNS, tACS) methods, Neuropsychol. Rehabil. 21 (5) (2011) 602–617, https://doi.org/10.1080/09602011.2011.557292.
[63] G. Perceval, A.K. Martin, D.A. Copland, M. Laine, M. Meinzer, High-definition tDCS of the temporo-parietal cortex enhances access to newly learned words, Sci. Rep. 7 (1) (2017) 1–9, https://doi.org/10.1038/s41598-017-17279-0.
[64] G. Perceval, A.K. Martin, D.A. Copland, M. Laine, M. Meinzer, Multisession transcranial direct current stimulation facilitates verbal learning and memory consolidation in young and older adults, Brain Lang. 205 (August 2019) (2020), 104788, https://doi.org/10.1016/j.bandl.2020.104788.
[65] E. Peristeri, I.M. Tsimpli, A. Sorace, K. Tsapkini, Language interference and inhibition in early and late successive bilingualism, Bilingualism 21 (5) (2018) 1009–1034, https://doi.org/10.1017/S1366728917000372.
[66] R. Polanía, M.A. Nitsche, C.C. Ruff, Studying and modifying brain function with non-invasive brain stimulation, in: Nature Neuroscience, Vol. 21, Nature Publishing Group,, 2018, pp. 174–187, https://doi.org/10.1038/s41593-017-0054-4.
[67] G. Prete, A. D'Anselmo, L. Tommasi, A. Brancucci, Modulation of the dichotic right ear advantage during bilateral but not unilateral transcranial random noise stimulation, Brain Cogn. 123 (January) (2018) 81–88, https://doi.org/10.1016/j.bandc.2018.03.003.
[68] S.M. Rampersad, A.M. Janssen, F. Lucka, U. Aydin, B. Lanfer, S. Lew, C.H. Wolters, D.F. Stegeman, T.F. Oostendorp, Simulating transcranial direct current stimulation with a detailed anisotropic human head model, IEEE Trans. Neural Syst. Rehabil. Eng. 22 (3) (2014) 441–452, https://doi.org/10.1109/TNSRE.2014.2308997.
[69] T. Reed, R.C. Kadosh, Transcranial electrical stimulation (tES) mechanisms and its effects on cortical excitability and connectivity, in: In *Journal of Inherited Metabolic Disease*, Vol. 41, Springer,, Netherlands, 2018, pp. 1123–1130, https://doi.org/10.1007/s10545-018-0181-4.
[70] J. Reis, H.M. Schambra, L.G. Cohen, E.R. Buch, B. Fritsch, E. Zarahn, P.A. Celnik, J. W. Krakauer, Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation, Proc. Natl. Acad. Sci. USA 106 (5) (2009) 1590–1595, https://doi.org/10.1073/pnas.0805413106.
[71] E. Santarnecchi, A.K. Brem, E. Levenbaum, T. Thompson, R.C. Kadosh, A. Pascual-Leone, Enhancing cognition using transcranial electrical stimulation, Curr. Opin. Behav. Sci. 4 (2015) 171–178, https://doi.org/10.1016/j.cobeha.2015.06.003.
[72] B. Sehm, J. Kipping, A. Schaefer, A. Villringer, P. Ragert, A comparison between uni-and bilateral tDCS effects on functional connectivity of the human motor cortex, Front. Hum. Neurosci. 7 (APR 2013) (2013) 1–7, https://doi.org/10.3389/fnhum.2013.00183.
[73] B.A. Simonsmeier, R.H. Grabner, J. Hein, U. Krenz, M. Schneider, Electrical brain stimulation (tES) improves learning more than performance: a meta-analysis, in: Neuroscience and Biobehavioral Reviews, Vol. 84, Elsevier Ltd, 2018, pp. 171–181, https://doi.org/10.1016/j.neubiorev.2017.11.001.
[74] J.G. Snodgrass, M. Vanderwart, A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity, Journal of Experimental Psychology: Human Learning and Memory 6 (2) (1980) 174–215, https://doi.org/10.1037/0278-7393.6.2.174.
[75] A. Snowball, I. Tachtsidis, T. Popescu, J. Thompson, M. Delazer, L. Zamarian, T. Zhu, R. Cohen Kadosh, Long-term enhancement of brain function and cognition using cognitive training and brain stimulation, Curr. Biol. 23 (11) (2013) 987–992, https://doi.org/10.1016/j.cub.2013.04.045.
[76] R. Sparing, M. Dafotakis, I.G. Meister, N. Thirugnanasambandam, G.R. Fink, Enhancing language performance with non-invasive brain stimulation-a transcranial direct current stimulation study in healthy humans, Neuropsychologia 46 (1) (2008) 261–268, https://doi.org/10.1016/j.neuropsychologia.2007.07.009.
[77] K. Tanaka, B. Ross, S. Kuriki, T. Harashima, C. Obuchi, H. Okamoto, Neurophysiological evaluation of right-ear advantage during dichotic listening, Front. Psychol. (2021) *12*, https://doi.org/10.3389/fpsyg.2021.696263.
[78] D. Terney, L. Chaieb, V. Moliadze, A. Antal, W. Paulus, Increasing human brain excitability by transcranial high-frequency random noise stimulation, J. Neurosci. 28 (52) (2008) 14147–14155, https://doi.org/10.1523/JNEUROSCI.4248-08.2008.
[79] H. Thair, A.L. Holloway, R. Newport, A.D. Smith, Transcranial direct current stimulation (tDCS): a Beginner's guide for design and implementation, Front. Neurosci. 11 (NOV) (2017), https://doi.org/10.3389/fnins.2017.00641.
[80] T. Thomsen, L.M. Rimol, L. Ersland, K. Hugdahl, Dichotic listening reveals functional specificity in prefrontal cortex: An fMRI study, NeuroImage 21 (1) (2004) 211–218, https://doi.org/10.1016/j.neuroimage.2003.08.039.
[81] Trans Cranial Technologies. (2012). 10 / 20 System Positioning. Gloucester Road, 2410, 77–79.
[82] Urbaniak, G.C., & Plous, S. (2013). Research Randomizer (4.0). http://www.randomizer.org/.
[83] S.J. Westwood, C. Romani, Null effects on working memory and verbal fluency tasks when applying anodal tDCS to the inferior frontal gyrus of healthy participants, Front. Neurosci. 12 (MAR) (2018) 1–19, https://doi.org/10.3389/fnins.2018.00166.
[84] S.J. Westwood, A. Olson, R.C. Miall, R. Nappo, C. Romani, Limits to tDCS effects in language: Failures to modulate word production in healthy participants with frontal or temporal tDCS, Cortex 86 (2017) 64–82, https://doi.org/10.1016/j.cortex.2016.10.016.
[85] J.H. Woo, H. Choi, Systematic review for AI-based language learning tools, ArXiv Prepr. ArXiv 2111 (2021) *04455*.
[86] A.J.J. Woods, A. Antal, M. Bikson, P.S.S. Boggio, A.R.R. Brunoni, P. Celnik, L.G. G. Cohen, F. Fregni, C.S.S. Herrmann, E.S.S. Kappenman, H. Knotkova, D. Liebetanz, C. Miniussi, P.C.C. Miranda, W. Paulus, A. Priori, D. Reato, C. Stagg, N. Wenderoth, M.A.A. Nitsche, A technical guide to tDCS, and related non-invasive

brain stimulation tools, Clin. Neurophysiol. 127 (2) (2016) 1031–1048, https://doi.org/10.1016/j.clinph.2015.11.012.
[87] World Medical Association, World medical association declaration of Helsinki ethical principles for medical research involving human subjects, JAMA: J. Am. Med. Assoc. 310 (20) (2013) 2191–2194, https://doi.org/10.1001/jama.2013.281053.
[88] L. Xia, T.H. Bak, A. Sorace, M. Vega-Mendoza, Interference suppression in bilingualism: stimulus-stimulus vs. stimulus-response conflict, Bilingualism (2021), https://doi.org/10.1017/S1366728921000304.