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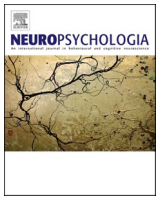

Enhancement of phonemic verbal fluency in multilingual young adults by transcranial random noise stimulation

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ABSTRACT

Several studies have analyzed the effects of transcranial direct current stimulation on verbal fluency tasks in non-clinical populations. Nevertheless, the reported effects on verbal fluency are inconsistent. In addition, the effect of other techniques such as transcranial random noise stimulation (tRNS) on verbal fluency enhancement has yet to be studied in healthy multilingual populations. This study aims to explore the effects of tRNS on verbal fluency in healthy multilingual individuals. Fifty healthy multilingual (Spanish, English and Basque) adults were randomly assigned to a tRNS or sham group. Electrodes were placed on the left dorsolateral prefrontal cortex and left inferior frontal gyrus. All participants performed phonemic and semantic verbal fluency tasks before, during (online assessment) and immediately after (offline assessment) stimulation in three different languages. The results showed significantly better performance by participants who received tRNS in the phonemic verbal fluency tasks in Spanish (in the online and offline assessment) and English (in the offline assessment). No differences between conditions were found in Basque nor semantic verbal fluency. These findings suggests that tRNS on the left prefrontal cortex could help improve phonemic, yet not semantic, fluency in healthy multilingual adults.

1. Introduction

Nowadays, it is becoming increasingly common to speak more than one language; in fact, in many regions and countries around the world, it is widespread for people to use two or more languages in their daily lives (Simons et al., 2022). This phenomenon is known as multilingualism. Multilingualism is a complex concept involving different dimensions (e.g., individual vs. social, proficiency vs. use, bilingualism vs. multilingualism), and is defined in different ways (Bot, 2019; Cenoz, 2013). However, the term multilingual is commonly used to refer to someone who uses or is proficient in more than one language (Clyne, 2017).

Multilingualism (or bilingualism) has been the subject of study by many disciplines for decades, both at the individual and collective level (Cenoz, 2013). At the individual level, there is a wealth of studies on the effects that multilingualism may have on language processing (e.g., verbal fluency) and executive functions (Anastassiou, 2020; Zeng et al., 2019). However, these are often investigated separately despite the fact that both involve common higher order cognitive processes (Friesen et al., 2015; Luo et al., 2010; Zeng et al., 2019), as well as common underlying brain areas, such as different regions of the left prefrontal cortex (e.g., left dorsolateral prefrontal cortex, left inferior frontal gyrus) (Bialystok et al., 2012; Gilbert and Burgess, 2008; Swick et al., 2008; Weiss, 2003). For example, authors such as Zeng et al. (2019) reported evidence of the correlation between bilingualism, verbal fluency, and executive functions throughout one's lifespan by using different neuropsychological tests. A strong correlation was found between language processes and executive functions, and better performance observed in bilingual children and older adults, which also indicates the influence of bilingualism on these processes during developmental changes (Zeng et al., 2019). It is important to note that numerous studies that have compared cognitive differences, such as executive functions and language, between bilinguals and multilinguals (Quinteros Baumgart and Billick, 2018), have not observed significant differences between the two populations (Achaa-Amankwaa et al., 2023; Guðmundsdóttir and Lesk, 2019; Halsband, 2006; Vega-Mendoza et al., 2015). The observed difference has been a greater protection of cognitive function throughout aging in multilinguals (Guðmundsdóttir and Lesk, 2019; Quinteros Baumgart and Billick, 2018).

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Several studies examining language processes and executive functions in bi/multilinguals use phonemic and semantic verbal fluency tests as a measure (Lehtonen et al., 2018). Both tasks require the use of different cognitive processes involving linguistic processing and executive control; however, the cognitive effort demanded by each task is slightly different (Luo et al., 2010; Shao et al., 2014). The phonemic task is thought to demand greater executive control, where the person must suppress associative activation related to the target word and generate new strategies to continue retrieving words beginning with the target letter (Luo et al., 2010; Strauss et al., 2006). The semantic task, however, demands an association strategy for word retrieval and is mostly related to verbal ability (Luo et al., 2010; Shao et al., 2014). In fact, several neuroimaging studies in healthy populations have observed an overlap of brain circuits when performing both fluency tasks, albeit not identical. Letter fluency (or phonemic fluency) has also been found to correlate more with the posterior-dorsal area, L-IFG, pre-supplementary motor area and left caudate; whereas semantic verbal fluency is associated with more antero-ventral activation in the left inferior frontal gyrus (L-IFG) (Costafreda et al., 2006; Grogan et al., 2009; Katzev et al., 2013).

When studying the performance of bilinguals and multilinguals in verbal fluency tasks, the results obtained are mixed, sustaining the debate surrounding the advantage or disadvantage of bilingualism/multilingualism in different cognitive areas (Bialystok et al., 2012; García et al., 2020; Lehtonen et al., 2018). Specifically, some studies have observed similar or even worse performance ("disadvantage") by bilinguals/multilinguals compared to monolinguals in verbal fluency tasks (especially in semantic verbal fluency). It could be hypothesized that this may be due to bilinguals' poorer knowledge of vocabulary or the difficulty in suppressing cross-language interference (especially where there is a difference in language dominance) (Giezen and Emmorey, 2017; Marsh et al., 2019; Sandoval et al., 2010). Conversely, other studies have reported better performance by bilinguals/multilinguals in verbal fluency tasks compared to monolinguals, especially in phonemic verbal fluency, indicating that this advantage may be due to higher executive performance, a feature previously associated with bilingualism (Bialystok et al., 2009, 2004; Chung-Fat-Yim et al., 2019; Craik et al., 2010; Luo et al., 2010; Stocco et al., 2014). Finally, other studies have shown that advantage or disadvantage in verbal fluency tasks depends on several crucial factors, such as the developmental stage, with greater bilingual advantage observed in children and older adults (Zeng et al., 2019); a wider vocabulary range (Pino Escobar et al., 2018); better language proficiency in bilinguals/multilinguals or age of language acquisition, the earlier the acquisition, the greater the advantage (Blumenfeld et al., 2016; Luo et al., 2010; Vega-Mendoza et al., 2015; Yow and Li, 2015).

Over the years and with technological developments, new tools have been introduced in verbal fluency studies, including the application of non-invasive electrical brain stimulation (tES) techniques in both clinical and non-clinical populations. Transcranial electrical stimulation techniques allow the non-invasive modulation of neuronal activity through the application of a weak electrical current by means of different conductive electrodes (e.g., saline-soaked sponges, ring electrodes with conductive gel or hydrogels) placed on the scalp (O'Leary et al., 2021; Paulus, 2011; Woods et al., 2016), which are usually used to enhance different motor, visual, auditory, and cognitive skills in non-clinical populations. There are different types of tES, the main difference between them being the way in which the weak electrical current is delivered (Paulus, 2011). The most popular and widely used is transcranial direct current stimulation (tDCS), which modulates neuronal activity by using a weak direct current (1–2 mA) (Nitsche and Paulus, 2000; Woods et al., 2016). Nevertheless, transcranial random noise stimulation (tRNS) is a technique which has several characteristics that clearly differentiate it from other types of tES. The most notable is the way in which the weak current of tRNS is applied, doing so by randomly alternating the electrical current's intensity and frequencies of the electrical current, ranging from low (0.1–100Hz) to high (101–640Hz) (Terney et al., 2008). Another distinctive feature of tRNS is the current's polarity, as it is neither anodal nor cathodal (Miniussi and Ruzzoli, 2013), allowing two different brain areas to be stimulated by two different electrodes at the same time. Furthermore, several studies have reported that tRNS causes physiological aftereffects that favor increased cortical excitability post-stimulation, which can last up to 60 min, especially when the full frequency spectrum is applied (Moret et al., 2019; Terney et al., 2008; van der Groen et al., 2022). Moreover, it has also been observed that tRNS seems to have greater neuromodulatory influence compared to other tES, which may favor the prolongation of its possible beneficial effects a posteriori on behaviors or cognitive skills (Inukai et al., 2016; van der Groen et al., 2022).

Regarding studies on tES and verbal fluency, as far as the authors are aware, no studies have investigated the effects of tRNS on verbal fluency tasks, especially in bilingual populations. It is more common to find studies that focus on assessing the effects of tDCS on monolinguals (Price et al., 2015) or bi/multilinguals, and that center on reading or enhancement language switching skills (Bhattacharjee et al., 2019, 2020; Liu et al., 2020; Radman et al., 2018). In any case, the left dorsolateral prefrontal cortex (L-DLPFC) and L-IFG are often targeted for stimulation (Vannorsdall et al., 2012); mainly due to their key association with verbal fluency, language learning, working memory, bilingual language switching and cognitive control (Abutalebi and Green, 2007; Brunoni and Vanderhasselt, 2014; Cargnelutti et al., 2019; Fiori et al., 2018; Gbadeyan et al., 2016; Jost et al., 2020; Wang et al., 2018). However, the results obtained are often mixed. Some studies find positive effects in both semantic and phonemic verbal fluency tasks (Cattaneo et al., 2011; Iyer et al., 2005; Meinzer et al., 2012), while others report null effects in both verbal fluency tasks (Ehlis et al., 2016; Klaus and Hartwigsen, 2020).

In bilingualism specifically, one study observed positive tDCS effects (anodal electrode on the DLPFC and return electrode on the right supraorbital area, rSO) only in the participants' native language, while no effects were noted in their second language (L2) (Radman et al., 2018). Given the lack of consistent and robust results on the effects of tDCS on verbal fluency, it has been hypothesized that this may be due to the characteristics of the protocol used for non-clinical samples, be it the stimulation parameters, type of tES used or even electrode placement (Klaus and Hartwigsen, 2020; Vannorsdall et al., 2016). In fact, regarding the electrode set-up, it is common to place the electrodes bilaterally (two electrodes, one on each cerebral hemisphere) in language studies (Santarnecchi et al., 2015). However, some authors have previously proposed the use of a unilateral set-up, placing both electrodes on the same hemisphere, which could improve focus on targeting brain area of interest and provide more unequivocal results (Klaus and Schutter, 2018). Nevertheless, few studies have used different montages on verbal fluency studies other than the conventional bilateral set-up previously described. For example, Penolazzi et al. (2013) compared the effects of four set-up types (frontal, fronto-temproral, bilateral and unilateral) on verbal fluency in healthy adults using anodal tDCS (2 mA current, 20 min). Better performance was observed in post-stimulation semantic verbal fluency with the frontal montage (anodal stimulation on the left frontal cortex and cathodal on the rSO), thus demonstrating the relevance of establishing suitable stimulation protocols (Penolazzi et al., 2013).

Therefore, the main aim of this study was to analyze the effects of tRNS on verbal fluency tasks (phonological and semantic) in three different languages (Spanish, English and Basque) in a group of healthy multilingual adults from the Basque Country, by applying unilateral tRNS that simultaneously stimulates the L-DLPFC and L-IFG areas. In addition, the studies examine the possible influence of performance in executive functions (Stroop test) on the performance of verbal fluency tasks post-stimulation. To this end, performance in the Stroop test is tested as to whether it could mediate effect of stimulation on the performance in verbal fluency tasks. In addition, it was hypothesized that

the results previously reported by other studies conducted in bilingual population can be transferred to the sample of the present study (bi/multilingual), since previous studies have shown similarities in language processing at the brain level (husband), so that the tRNS setup applied may be beneficial for both profiles.

The information that will be reported in the present study could provide evidence-based data on the effects of tRNS on the processing of language skills in bilingual individuals, as well as possible implications of this tool in this population and how these data could be translated to its application for language disorders in individuals who know more than one language. Additionally, it will provide relevant information about the possibility of applying a different tRNS stimulation setup in studies with bilingual and multilingual population in linguistic tasks such as verbal fluency, applying this type of stimulation simultaneously in brain areas previously studied independently and with tDCS. In addition, this is the first study that specifically analyzes the effects of unilateral tRNS in multilinguals with the Basque language, providing evidence-based data on the Basque language and tRNS stimulation effects.

Therefore, it is important to note that in this study we will focus on the population from a multilingual environment: the Basque Country. In the Basque Country there are two official languages (Basque and Spanish, that children learn at home as well as at school.), and a third language is taught from childhood (basic English is taught in schools from the age of seven). In addition, from the age of 12, some schools offer students the possibility of learning a fourth language, usually French or German. Basque and Spanish are used in everyday life, in different contexts (e.g.: leisure, school, work, media, entertainment, etc.), while English tends to be used in the school environment. Therefore, it is common for locals in this region to be familiar with language learning, despite having different levels of language proficiency (unbalanced bilinguals).

2. Material and methods

2.1. Participants

To estimate the required sample size for the study, the G*Power 3.1 software (Faul et al., 2009) was used. For an a priori F-test analysis (ANOVA: Repeated measures, between factors) for two groups, with a medium effect size ($d = 0.5$), a 0.05 error probability was estimated and to achieve a 0.95 alpha power, the program set a minimum sample size of 42 participants. Nevertheless, it was considered appropriate to increase the sample in this study so as to achieve greater statistical power. Thus, 50 young adults were recruited (37 females, mean age 23.54 ± 6.76, mean years of education 15.40 ± 3.28). The inclusion criteria included: (1) being aged between 18 and 60 years old, (2) being a native Spanish speaker and (3) having learnt English and/or Basque. Participants reported no psychiatric or neurological disorders and were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were native Spanish speakers, of which 12 (24%) were bilingual (Spanish and English) and 38 (76%) were multilingual (Spanish, Basque and English). Furthermore, participants (%) reported the following order of acquisition of each language: Spanish, Basque and English (88.5%); Spanish, English and Basque (3.8%); Spanish/Basque and English (1.9%) and Spanish and English (5.8%). The participant's age of acquisition of each language, subjective proficiency and frequency of use, and exposure to each language were assessed. It is important to highlight that most of the participants were exposed to Basque as soon as they entered school. In the Basque Country, learning Basque is compulsory from an early age, however, after finishing school, there were some volunteers who did not learned it well or even, due to disuse, their level of Basque became so low that they were not considered multilingual. However, they did decide to continue with their English language studies. All participants had normal or corrected-to-normal vision.

Exclusion criteria included: (1) suffering from frequent or severe headaches or migraines; (2) previous history of brain surgery; (3) pregnancy; (4) previous history or presence of neurological disorder or injury (severe brain injury, brain stroke, epileptic or convulsive seizure), and (5) the presence of any type of metal implant in the brain.

2.2. Measures

2.2.1. The Edinburgh Handedness inventory

Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971). In this test, participants are asked to indicate their preference of hand use for 10 everyday activities. Scores ranged from 100 (perfectly right-handed) to − 100 (perfectly left-handed).

2.2.2. The stroop color and word test (SCWT)

SCWT is an individually applied neuropsychological test that is widely used for the assessment of different cognitive processes, both in clinical and non-clinical populations (Golden, 2010). The test consists of three tasks presented on three different sheets. The participant has to read the content of these sheets correctly and as quickly as possible. The first two tasks are considered "congruent conditions" in which they must first read different color names written in black ink (word), while on the second sheet, they must name different colors that appear (color) (Bugg et al., 2008; Pan et al., 2022; Scarpina and Tagini, 2017). Finally, the third task corresponds to an incongruent condition, where the individual must name the color of the ink and not read the word (color-word). In the latter case, the meaning of the word does not correspond to the color of the ink (e.g., the word green is written in red ink). In this study, it was used to evaluate the processing speed and cognitive flexibility of the participants. The overall score's internal consistency was high (Cronbach's alpha = 0.80).

2.2.3. Verbal fluency tasks

The verbal fluency test was used for assessment and was divided into two parts: phonemic fluency and semantic fluency. The verbal fluency tasks were applied in two different languages for the bilingual participants (Spanish and English, N = 12), and three different languages for the multilingual participants (Spanish, Basque and English; N = 38). All phonemic (letters) and semantic (categories) tasks were counterbalanced across participants.

- Phonemic fluency: participants had to produce words starting with a specific letter in 1 min. For this task, letters "P", "M", "R", "F", "A", and "S", were used for Spanish; "L", "F", "A", "S"; and "C", for English; and "E", "A" and "B" were used for Basque. Letters "P", "M", "R", "F", "A", and "S" are frequently used by Spanish speakers. The letters were selected based on their high frequency of use in each language and the fact that all participants were Spanish-speakers (Casals-Coll et al., 2013; Olabarrieta-Landa, 2017).
- Semantic fluency: For the semantic task, participants said within 1 min all the possible words belonging to the given semantic category in 1 min. In this case, the categories used for the three languages were animals, professions, and fruits and vegetables.

2.2.4. Language experience and proficiency questionnaire (LEAP-Q)

To assess the participants' linguistic profiles, the LEAP-Q was used in paper-and-pencil format. This self-reported questionnaire is a validated tool enabling a detailed assessment and description of language proficiency, exposure, immersion, and use of preference in different contexts, as well as other aspects of the individual's linguistic profile that provide relevant information about the languages spoken by the individual (Kaushanskaya and Marian, 2009; Marian et al., 2007).

2.2.5. Transcranial electrical stimulation adverse effects questionnaire

Participants completed a 12-item questionnaire at the end of the

experiment to identify any reported adverse effects (including headache, scalp pain, sore throat, tingling or itchiness of the skin, a burning sensation on the skin, rashes, dizziness, numbness, mood change, concentration problems and phosphenes).

2.3. Electrical stimulation protocol: tRNS

tRNS 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. The electrodes were placed on the L-DPFC and L-IFG areas (F3 and FT7-F7 electrodes respectively according to the International 10–20 Electrode Placement System), delivering a 1.5 mA current (100–500 Hz). The current was applied via two saline-soaked (5 ml approximately per sponge), 8 cm^2 circular sponges. In the sham condition, the same electrode placement was performed, and the current was applied using a 30s ramp-up followed 20 min after by a 30s ramp-down of activity. Electrode impedance was checked before and during stimulation application so as ensure that it was under 10 kΩ. Electrodes were placed following the International 10–20 System (Trans Cranial Technologies, 2012). The electrodes placement's stimulated electric field for each condition can be seen in Fig. 1.

2.4. Study design and procedure

The study followed a randomized, double blind, sham-controlled design. The participants were randomly allocated to two different condition groups: stimulation or placebo using a computer-generated randomization (randomizer.org). Half of the group thus received tRNS and the other half the sham condition. In addition, the letter and category order of the verbal fluency tests for both conditions were counterbalanced across participants.

All participants were tested individually in a single session. At the beginning of the assessment, participants were also asked if they had slept more or less than normal or drunk more or fewer stimulant beverages than usual. The session was divided into three parts: (1) baseline, (2) online and (3) offline assessment (see Fig. 2 for procedure details). In the first part, participant baseline scores were assessed using the SCWT: the phonemic fluency (two letters for Spanish and English, one letter for Basque) and semantic fluency (one category per language) tasks. Then, in the second part of the assessment, the participant completed the LEAP-Q questionnaire and, while receiving 20 min of tRNS, performed the semantic and phonetic (two letters for Spanish and English, one letter for Basque) fluency tasks and Stroop test. In the third part, the neoprene cap was removed, and after a short rest, the participants completed the verbal fluency tasks with no stimulation (offline). Finally, the session concluded with the questionnaire on adverse effects of the stimulation.

2.5. Statistical analysis

The statistical analyses were carried out using SPSS version 27 for Windows (IBM Corp, 2020). Data normality was calculated by the Shapiro-Wilk test. Descriptive analyses were performed to show participant baseline characteristics in greater detail. Analysis of variance (ANOVA) and Chi-squared tests ($\chi 2$) were also used to analyze between-group differences according to age, years of education, handedness, number of hours slept, and stimulants consumed (e.g., coffee, tea, energy drinks, etc.), and their baseline performance in the verbal fluency tasks and Stroop test. T-test analyses were also carried out to detail the participants' linguistic profiles.

Analyses of covariance (ANCOVA) were performed to compare language scores between the groups (tRNS group and sham group), with the online and offline language scores as dependent variables and baseline assessment language scores as covariates. Bonferroni correction was used. *P*artial eta-squared (η_p^2) effect size was reported. For the intervals of interpretation of η_p^2, 0.01 was considered small effect, 0.06 indicated medium effect and 0.14 large effect (Cohen, 1988).

In addition, mediation and moderation analyses were conducted using PROCESS macro (V4.0) for SPSS (Hayes, 2018) to test whether SCWT performance could mediate or influence, respectively, the relationship between stimulation effects and verbal fluency performance. To carry out the mediation analyses, change scores from the SCWT and verbal fluency tests were used. The significance level was set at 0.05. The Bonferroni method was used to correct multiple comparisons.

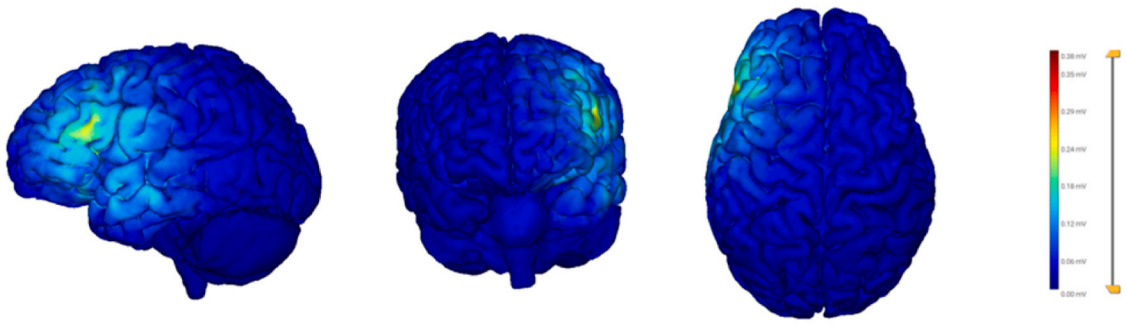
3. Results

3.1. Sociodemographic characteristics

The baseline variables of the groups can be seen in Table 1. There were no significant differences between the groups in age, years of education, or sex. There were no statistically significant differences between groups in the number of stimulant drinks consumed (e.g., coffee, tea, energy drinks) or number of hours slept prior to the evaluation.

3.2. Linguistic profile: LEAP-Q

Participants' linguistic profiles can be seen in Table 2. No significant



Note: Electrode montage influence map provided by Stim Weaver software (Neuroelectrics Inc., Barcelona) based on a realistic head model (Miranda et al., 2013), Stimulated area: F3 and FT7-F7 electrodes.

Fig. 1. Electrode placement for the study's stimulation (tRNS).
Note: Electrode montage influence map provided by Stim Weaver software (Neuroelectrics Inc., Barcelona) based on a realistic head model (Miranda et al., 2013), Stimulated area: F3 and FT7-F7 electrodes.

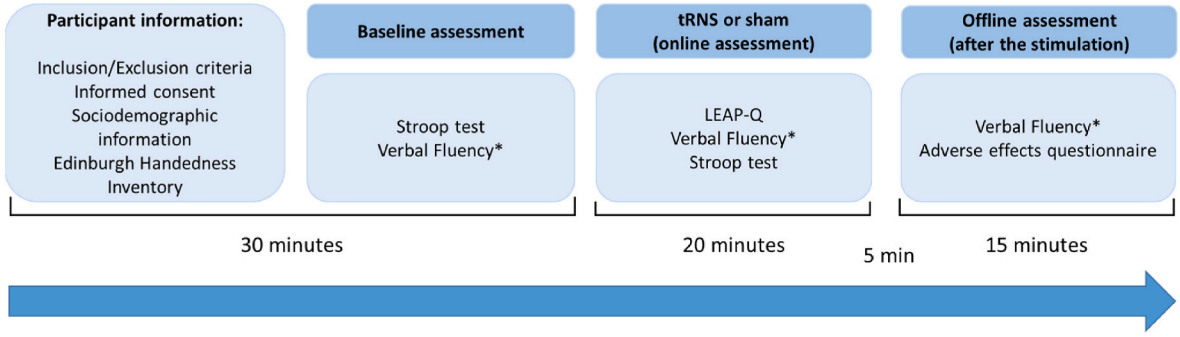


Fig. 2. General study procedure.
Note: Verbal Fluency* = phonemic and semantic tasks were counterbalanced across participants, 5 min = participants had a 5-min break after stimulation.

Table 1
Baseline demographic characteristics of participants according to the assigned group (stimulation or placebo).

	tRNS group (n = 25)		Sham group (n = 25)			*p*
	Mean (Range)	SD	Mean (Range)	SD	Statistic	
Age	24.84 (18–47)	7.93	22.24 (18–30)	5.19	$F = 1.47$	0.17
Years of education	15.40 (12–23)	3.29	15.40 (11–24)	3.34	$F = 0.00$	1.00
Sex: n (%)					$\chi^2 = 2.59$	0.11
Female participants	21 (84%)		16 (64%)			
Male participants	4 (16%)		9 (36%)			
Edinburgh Handedness	13.96 (10–43)	6.61	13.88 (10–28)	4.23	$F = 0.00$	0.96
Number of slept hours	6.68 (4–9)	1.18	7.20 (5–9)	0.91	$F = 3.03$	0.08
Number of stimulants	0.56 (0–2)	0.71	0.68 (0–2)	0.69	$F = 0.36$	0.55

Note: SD = Standard Deviation.

differences were observed in the age of language acquisition of any of the languages (Basque and English) between the groups. Likewise, the results obtained by participants were very similar, with no differences in the language items assessed by the LEAP-Q. However, in Basque, statistically significant differences were observed between the groups in the item "listening to radio/music" in the domain of contribution to language learning ($p = 0.01$) and exposure and use ($p = 0.03$). These results seem to indicate a greater contribution to Basque language learning from listening to music and greater exposure to music in the sham group than in the active stimulation group. Therefore, both items were controlled for in subsequent analyses to account for this difference.

3.3. trns effects on verbal fluency and the scwt

All the verbal fluency test results obtained by participants are shown in Tables 3–4. No differences were reported between groups in baseline performance in the verbal fluency tasks (F ranged from 0.03 to 1.11 and p from 0.297 to 0.956).

In the phonemic fluency test, statistically significant differences were observed between the conditions (tRNS and sham) in Spanish during stimulation ($F = 5.31$, $p = 0.026$) and afterwards (offline assessment) ($F = 6.44$, $p = 0.015$), and in English only offline ($F = 10.80$, $p = 0.002$). In English, marginally significant results were observed during phonemic

Table 2
Language profile of the participants (scores obtained from the LEAP-Q).

	tRNS Basque		Sham Basque			tRNS English		Sham English		
Variable	Mean	SD	Mean	SD	*p*	Mean	SD	Mean	SD	*p*
Age of acquisition (age)	2.55	2.26	3.33	1.56	0.94	7.36	6.82	6.40	2.24	0.51
Self-evaluation										
Speaking (1–10)	6.10	2.79	5.71	2.25	0.61	6.12	2.31	6.16	2.11	0.95
Comprehension (1–10)	7.65	2.10	7.71	2.03	0.93	6.92	2.45	7.40	2.23	0.47
Reading (1–10)	7.70	1.95	7.60	2.04	0.85	7.04	2.19	7.60	1.58	0.31
Contribution to learning										
Interacting with friends (0–10)	3.90	3.77	4.50	2.75	0.55	2	3.01	1.40	2.65	0.46
Interacting with family (0–10)	2.15	2.98	2.17	3.13	0.99	1.92	2.80	1.80	3.24	0.89
Reading (0–10)	5.85	2.85	5.29	2.82	0.52	5.12	3.51	5.08	3.45	0.97
Language self-learning (0–10)	6	3.01	5	3.50	0.32	7.08	2.93	6.68	3.53	0.66
Watching TV (0–10)	4.80	3.33	5.58	2.40	0.37	5.68	3.32	4.32	3.37	0.16
Listening to radio/music (0–10)	2.25	2.83	4.71	3.04	**0.01***	4.64	3.67	4.32	3.18	0.74
Exposure and use										
Interacting with friends (0–10)	3.30	3.69	2.54	2.72	0.44	2.32	2.97	1.68	2.73	0.43
Interacting with family (0–10)	1.25	2.02	1.29	2.11	0.95	0.88	2.03	0.48	1.69	0.45
Reading (0–10)	3.10	4.05	2.00	2.55	0.28	5	3.16	4.72	3.95	0.78
Language self-learning (0–10)	1.65	3.05	2.54	3.36	0.37	2.40	3.37	1.96	3.42	0.65
Watching TV (0–10)	2.05	2.80	1.79	2.37	0.74	5.36	3.64	5.24	3.71	0.91
Listening to radio/music (0–10)	2.40	2.91	4.33	2.75	**0.03***	5.40	3.73	5.80	3.27	0.69

Note: M = Mean; SD= Standard Deviation; *$p < 0.05$.

Table 3
Participants' verbal fluency raw scores at baseline, online and offline assessment.

			tRNS Group (n = 25)		*Sham Group (n = 25)*	
Language	VF Task		M	SD	M	SD
Spanish	Phonemic	Baseline	31.72	5.82	29.68	7.72
		Online	35.60	7.18	30.32	7.38
		Offline	32.68	5.29	27.16	8.44
	Semantic	Baseline	20.76	5.32	21.44	6.08
		Online	23.04	7.41	21.56	4.87
		Offline	18.52	3.96	16.76	4.52
English	Phonemic	Baseline	18.52	3.43	17.44	5.56
		Online	17.84	5.16	14.44	6.52
		Offline	22.20	6.99	15.96	6.04
	Semantic	Baseline	13.36	4.88	12.28	5.48
		Online	10.16	3.54	8.28	3.56
		Offline	12.68	4.69	11.28	4.81
Basque†	Phonemic	Baseline	10.22	4.14	10.45	3.57
		Online	10.67	3.97	9.80	4.35
		Offline	12.44	4.30	10.95	3.69
	Semantic	Baseline	8.33	4.71	8.25	4.49
		Online	10.67	5.44	10.80	4.90
		Offline	9.89	5.37	8.30	5.55

Note: Baseline = reported participants scores before stimulation, Online = raw scores obtained during stimulation; Offline = raw scores obtained after stimulation; Basque† = in Basque, there were 20 participants in the placebo group and 18 participants in the tRNS group, *$p < 0.05$.

online assessment ($F = 3.75$, $p = 0.059$). Thus, the analyses indicate a higher number of words produced by participants who received the tRNS condition compared to the sham group in the native language (Spanish) and English. In Basque, no statistically significant differences were observed in the online and offline phonemic fluency test assessment, which may be due to the sample size used for this language, since better performance was observed in the tRNS ($M = 12.52$, $SE = 0.73$) group than in the sham group ($M = 10.88$, $SE = 0.70$) in the phonemic verbal fluency test when controlling for baseline scores. In the semantic verbal fluency test, no statistically significant differences were observed between the groups in any of the languages (Spanish, Basque or English), either during stimulation (online) or afterwards (offline).

Furthermore, in the SCWT, statistically significant differences were only observed in the color-word part ($F = 7.60$, $p = 0.008$) during stimulation (online assessment), showing a better performance of participants in only that part of the SCWT when receiving the tRNS condition compared to the sham condition. Therefore, in the rest of the Stroop test, the participants did not show statistically significant differences between the groups. Stroop test scores can be seen in detail in the supplementary material: Tables S1–S2.

3.4. Mediation and moderation analyses

Finally, on the one hand, the SCWT scores were examined as to whether they could mediate between participant performance in Spanish and English phonemic fluency and tRNS condition. The results show a non-significant, indirect stimulation effect on both languages' phonemic verbal fluency performance via the SCWT (Spanish: $b = -0.37$, $t = -1.78$, English: $b = 0.09$, $t = -1.91$) (see Fig. 3).

On the other hand, moderation analyses also were carried out to study whether the Stroop test scores could influence participant performance in Spanish and English phonemic fluency after having received tRNS. There was no statistically significant moderation of the SCWT performance variable that could explain the relationship between the condition received and phonemic verbal fluency performance in Spanish ($b = 0.08$, $SE = 00.36$, $t = 00.21$, $p = 00.82$), and in English ($b = -0.51$, SE = 0.32, $t = -1.6$, $p = 00.11$) (see details of the moderation analyses in Fig. 4).

3.5. Adverse effects

Participants reported no serious discomfort or unusual sensations on the scalp. Likewise, no statistically significant differences were observed between conditions in the reported adverse effects (all $X^2 \leq 2.08$, $p's \geq 0.081$). For further details, see the supplementary material: Table S3.

4. Discussion

The main objective of this study was to explore the effects of tRNS on the left prefrontal cortex in verbal fluency tasks in three different languages (Spanish, Basque and English) in healthy multilingual individuals. Moreover, the study analyzed whether SCWT performance could influence the effects of tRNS on verbal fluency task performance. The results obtained showed positive effects on the performance of participants receiving tRNS in phonemic fluency tasks in their native language (Spanish) both in online and offline assessments, and in English in the offline assessment, and marginally significantly in the online phonemic assessment. However, no differences were observed between the groups in the semantic fluency tasks in either language. Similarly, no differences were observed in the phonemic verbal fluency tasks in Basque. However, it is important to bear in mind, when interpreting the results, that fewer participants were tested in Basque than in Spanish and English.

As for the obtained positive effects of stimulation in this study, the data suggest that tRNS application focused on a left hemisphere region can significantly increase the number of words produced, especially in the native language of "unbalanced" (those more fluent in one language than the other) multilingual individuals. These results are consistent

Table 4
ANCOVA of the verbal fluency scores obtained by participants under stimulation or sham (online) and after stimulation (offline) controlling for baseline verbal fluency performance.

			tRNS Group (n = 25)		Sham Group (n = 25)		ANCOVA		
Language	VF Task		M	SE	M	SE	F	p	η_p^2
Spanish	Phonemic	Online	35.04	1.27	30.88	1.27	5.31	**0.026***	0.10
		Offline	32.14	1.23	27.69	1.23	6.44	**0.015***	0.12
	Semantic	Online	23.12	1.24	21.48	1.24	0.86	0.357	0.02
		Offline	18.58	0.83	16.70	0.83	2.53	0.118	0.05
English	Phonemic	Online	17.39	0.91	14.88	0.91	3.75	0.059	0.07
		Offline	21.87	1.20	16.28	1.20	10.80	**0.002***	0.18
	Semantic	Online	9.96	0.61	8.47	0.61	2.95	0.092	0.05
		Offline	12.56	0.93	11.41	0.93	0.74	0.393	0.01
Basque†	Phonemic	Online	10.87	0.84	9.62	0.79	1.06	0.310	0.03
		Offline	12.74	0.79	10.68	0.75	3.21	0.082	0.08
	Semantic	Online	10.98	1.03	10.52	0.96	0.09	0.756	0.00
		Offline	9.48	1.00	8.66	0.94	0.32	0.575	0.01

Note: Online = reported participants scores during the stimulation condition; Offline = participants scores after the stimulation condition; *M* = Marginal means; SE= Standard Error, Basque† = in Basque, there were 20 participants in the placebo group, and 18 participants in the tRNS group, *$p < 0.05$.

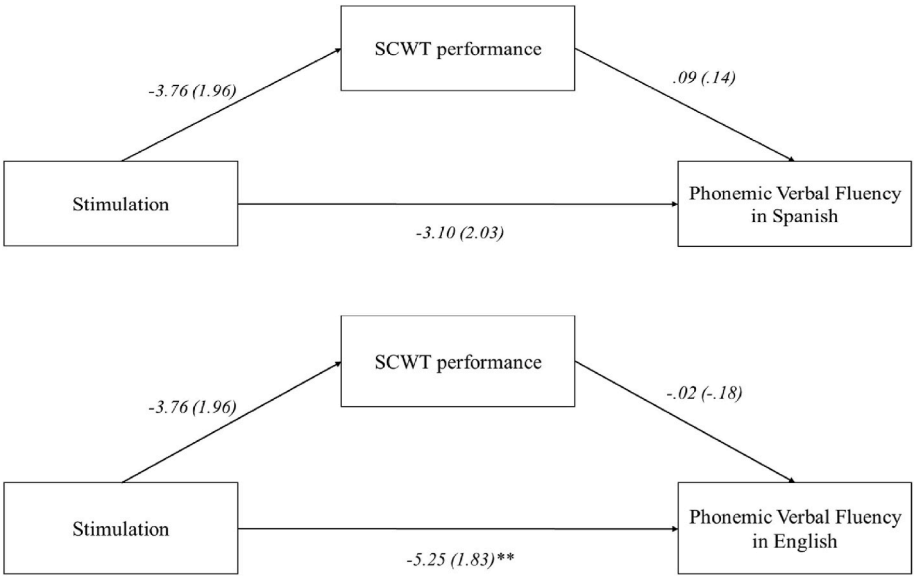


Fig. 3. Model of mediation of SCWT performance between stimulation and phonemic verbal fluency in Spanish and English.

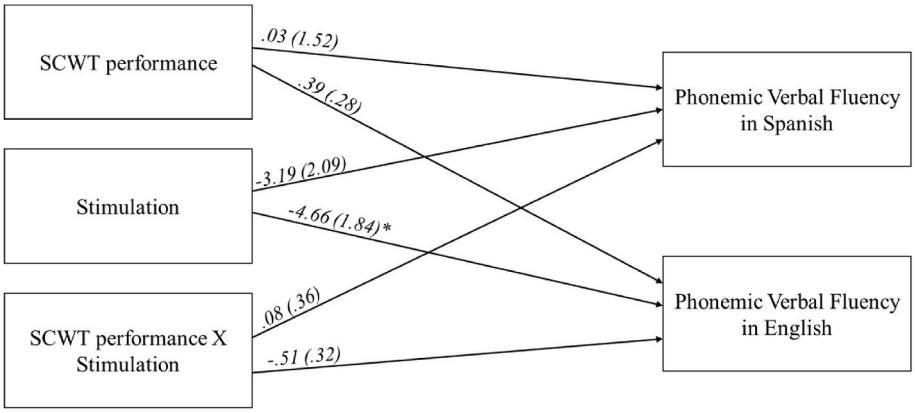


Fig. 4. Statistical moderator analysis diagram assessing the role of SCWT performance in the relationship between stimulation effects and phonemic verbal fluency performance in Spanish and English. Given values are non-standardized coefficients with standard errors in parentheses. *p ≤ 0.05. **p ≤ 0.001.

with previous studies where was observed a significant improvement in participants' phonemic fluency (in their native language) after 20 min of anodal tDCS when stimulation was applied to L-IFG (Pisoni et al., 2018), L-DLPFC (Cattaneo et al., 2011) or the frontotemporal region (Binney et al., 2018). In addition, the montage used in this study may have maximized the stimulation effect in the area of interest by focusing the electrical impulses on a left hemisphere region, in contrast to the bilateral montage, where stimulation tends to be more diffuse (Rampersad et al., 2014; Sehm et al., 2013). Therefore, based on previous literature highlighting the key role of the L-DLPFC and L-IFG in various linguistic and cognitive processes, it was expected that the same favorable effects would be observed in all participant language (Abutalebi and Green, 2007; de Bruin et al., 2014; Vannorsdall et al., 2012).

On the other hand, a major factor that may have influenced lower performance and no stimulation effect, especially in semantic verbal fluency compared to phonemic fluency, is the participants' multilingual profiles in themselves. According to the data collected in the language profile test, the participants in this study had "unbalanced" language proficiency, that is, the proficiency in the different languages was not the same, and previous authors have suggested that this weaker performance may be due to bilinguals' poorer knowledge of vocabulary or difficulty in suppressing cross-language interference (especially where there is a difference in language dominance) (Giezen and Emmorey, 2017; Marsh et al., 2019; Sandoval et al., 2010). It is therefore hypothesized that, in this case, knowledge of different languages may have somehow interfered with semantic fluency performance in the second and third language (e.g., code-switching difficulties) (Altarriba and Kazanas, 2017; Sandoval et al., 2010). Such results have been previously observed in a study by Radman et al. (2018), in which EEG and tDCS were applied to the L-DLPFC in a group of healthy bilingual adults (French as L1, and English as L2) with an "unbalanced" knowledge of the two languages. In their results, physiological changes by stimulation were observed in the participants' nerve activity, especially when L2 was used in different linguistic tasks. However, no behavioral improvements in the participants' performance were observed in verbal fluency tasks after applying tDCS (Radman et al., 2018). It is also relevant to mention that this hypothesis should not deemed definitive, as other studies analyzing performance in verbal fluency tasks by bilinguals compared to monolinguals (without stimulation) have reported contradictory results. On the one hand, there are studies that observed better performance by bilinguals in verbal fluency (both semantic and phonemic), especially when the task involved higher executive control (Friesen et al., 2015; Patra et al., 2020). Meanwhile other studies report similar or even weaker performance in verbal fluency (especially semantic verbal fluency) between monolinguals and bilinguals (bilinguals performing worse) (Blumenfeld et al., 2016; Portocarrero et al., 2007).

However, other studies have observed a difference in performance (higher, equal, or even lower) within the bilingual group itself (Friesen et al., 2015; Gollan et al., 2002; Luo et al., 2010). These latter studies highlight the relevance of considering factors such as the age of L2 acquisition, language proficiency, and age or amount of known vocabulary when assessing performance in verbal fluency tasks, etc. (Kheder and Kaan, 2021; Wauters and Marquardt, 2018; Zeng et al., 2019). Thus, in relation to the results obtained by this study, not having the same language proficiency across languages and a different level of vocabulary in each language may have affected performance in semantic verbal fluency tasks. (Bartolotti and Marian, 2012; Kaushanskaya and Marian, 2009; Maluch et al., 2016; Peristeri et al., 2018). Lastly, concerning the possible reasons for the lack of significant improvement in semantic verbal fluency, it was initially suggested that the area of interest stimulated could be an important factor, as well as the number of sessions received, which, in this case, was a single session. Regarding the number of sessions, the beneficial effects of stimulation seem to be more noticeable at a behavioral level when it comes to studies performing multiple stimulation sessions, compared to those performing a single session (Berryhill and Martin, 2018; van der Groen et al., 2022). Therefore, the enhancing effects on semantic verbal fluency could perhaps be observed after multiple stimulation sessions.

Another factor to highlight may be language characteristics. The language on which no apparently significant effect was observed was Basque. Basque is one of the oldest languages in Western Europe, prior to Indo-European languages, whose origin remains unknown (Gorrochategi-Churruca et al., 2018), and is specific to the Basque Country region in northern Spain and to the French Basque Country in south-west France. It is a complex language with completely different characteristics to English or Spanish. In fact, previous neuroimaging studies have shown slightly different brain activation to the use of English or Spanish in bilingual individuals that knew Basque when performing different linguistic tasks (e.g., reading) in an experimental setting (Brignoni-Perez et al., 2020; Nieuwland et al., 2012; Oliver et al., 2016), and other studies have proposed different possible brain pathways for each language in bilinguals (Bhattacharjee et al., 2020). Hence, perhaps the electrode setup used in this study is not ideal for this language. Furthermore, previous studies point to the importance of modifying assessment tests, such as verbal fluency tasks, for different languages such as Chinese (Eng et al., 2019). In our case, despite having used a previously standardized version of the verbal fluency test for Basque (Olabarrieta-Landa, 2017), no stimulation effect on this language was observed in either of the conditions. Finally, the lack of statistical significance in the Basque results may principally be due to the smaller sample size available compared to the Spanish and English sample.

Regarding the SCWT, significant improvement in response time for the color-word segment was observed in those participants receiving tRNS. These results are in line with a recent meta-analysis in which 45 single-session tDCS studies and a total of 75 effect sizes were analyzed (considering set-up type, stimulation intensity, task type, etc.), positive tDCS effects were observed over the SCWT, especially when the main electrode was applied to the L-DLPFC area (Schroeder et al., 2020). And, with a previous study that applied tDCS over the DLPFC of bilingual and monolingual adults to examine the role of DLPFC on control for between-language switching and nonlinguistic switching and whether the control enabled by DLPFC differs between bilinguals and monolinguals, were they reported a relevant role of DLPFC on bilingual picture-naming. (Vaughn et al., 2021). However, no effects on Stroop performance were observed in this study's mediation analyses, thus showing a lack of influence of SCWT performance on positive tRNS effects on verbal fluency. This may be mainly due to the sample's bilingualism. Previous studies have reported better SCWT performance in bilinguals when compared to monolinguals (Blumenfeld and Marian, 2014). However, all the participants in this study were bilingual, thus the possible difference in Stroop performance probably went undetected. This result is consistent with previous studies, which have found no significant differences in SCWT performance among bilinguals (Roselli et al., 2002). On the other hand, the lack of mediating effects of Stroop performance is consistent with some theories and studies that reported that the neural mechanisms of language control and executive control in bilinguals partially overlap (Jiao et al., 2022), which may indicate that performance in executive control may not be as crucial factor of language control in bilinguals.

When interpreting the results obtained, some limitations must be considered. First, despite having previously estimated the study sample with a statistical tool, it is believed that it would have been beneficial to further increase the number of participants to be able to observe the results obtained in greater detail. Second, although the results with similar, previous studies using tDCS were compared, comparing our results with a larger number of similar studies using tRNS would have been revealing, especially regarding verbal fluency performance. Thus, it would be worth replicating these studies in the future with different set-ups and non-invasive stimulation techniques other than tDCS.

In conclusion, this study provides relevant data on the effects of tRNS on verbal fluency tasks in multilingual individuals. Mixed results have been found, which add to the ongoing debate on the beneficial effects of non-invasive electrical stimulation techniques in cognition on healthy participants. However, despite this, the use of tRNS and other set-up types other than bilateral seem to help exploit this technique's beneficial effects on healthy individuals. Further research is required, as is the application of other non-invasive electrical stimulation techniques other than tDCS.

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Compliance with ethical standards

The study was approved by the Ethics Committee of the University of Deusto (Ref: ETK-40/18–19) and carried out in accordance with the Declaration of Helsinki guidelines for medical research involving human subjects (World Medical Association, 2013). Participants received no monetary compensation for their involvement in the research trial.

CRediT authorship contribution statement

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

Declaration of competing interest

The authors declare that there 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.

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Appendix A. Supplementary data

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