# Effects of non-invasive brain stimulation on foreign language learning processes

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Doctoral thesis presented by Yolanda Balboa Bandeira,

To obtain the degree of Doctor of Psychology by the University of Deusto

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Dr Javier Peña Lasa, coordinator of the Doctoral program in Psychology, member of the academic commission of the Doctoral program in Psychology, Assistant Professor of the Department of Psychology, director of the present thesis; and Dr Leire Zubiaurre Elorza, investigator of the Neuropsychology of Severe Medical Conditions research team, and Assistant Professor of the Department of Psychology at the University of Deusto, director of the present thesis, certify that the present thesis entitled **“Effects of non-invasive brain stimulation on foreign language learning processes”** represents an original research work, which is presented by Yolanda Balboa Bandeira in order to obtain the degree of Doctor.

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# Contents

**Foreword ... xxi**

**Glossary of Abbreviations ... xxiii**

**Glossary of Tables ... xxv**

**Glossary of Figures ... xxvii**

**1 Abstract ... 31**

1.1 Abstract ... 31

1.2 Resumen ... 33

**2 Introduction ... 37**

2.1 General framework: Use of techniques in the study of cognition ... 37

2.2 Non-invasive brain stimulation (NIBS): A Brief Overview ... 37

2.3 Transcranial electrical stimulation (tES) ... 38

2.3.1 Transcranial Direct Current Stimulation (tDCS) ... 40
2.3.2 Transcranial Alternating Current Stimulation (tACS) ... 45
2.3.3 Transcranial Random Noise Stimulation (tRNS) ... 47
2.4 tES and the study of cognition ... 50

2.4.1 tES on language learning studies ... 51
2.5 Bilingualism ... 55

2.5.1 Bilingualism and cognition ... 57
2.5.2 Bilingualism and verbal fluency ... 59
2.5.3 tES on bilingualism and verbal fluency studies ... 61
**3 Approach to the present thesis and objectives ... 65**

3.1 Study I ... 65

3.2 Study II ... 66

3.3 Study III ... 67

**4 Methods ... 71**

4.1 Study I ... 71

4.1.1 Inclusion criteria ........ 71
4.1.2 Literature search ........ 71
4.1.3 Study quality assessment ........ 75
4.1.4. Data extraction ........ 77
4.1.5. Statistical analysis ........ 77
4.2 Study II ........ 81
4.2.1 Participants ........ 81
4.2.2 Stimulus selection ........ 82
4.2.3 Experimental learning paradigm ........ 83
4.2.4 Materials and instruments ........ 84
4.2.5 Electrical stimulation protocol ........ 85
4.2.6 Study design and procedure ........ 87
4.2.7 Statistical analysis ........ 88
4.3 Study III ........ 89
4.3.1 Participants ........ 89
4.3.2 Materials and instruments ........ 90
4.3.3 Electrical stimulation protocol: tRNS ........ 91
4.3.4 Study design and procedure ........ 92
4.3.5 Statistical analysis ........ 93
**5 Results ........ 97**
5.1 Study I ........ 97
5.1.1 Characteristics of the included studies. ........ 97
5.1.2 Overall effects of tES on language learning success ........ 104
5.1.3 Effects of tES on response times. ........ 105
5.1.4 Duration of tES enhancement effects one week after stimulation ........ 105
5.1.5 Meta-regression analyses ........ 106
5.1.6 Publication bias ........ 106
5.1.7 Sensitivity analysis ........ 107
5.2 Study II ........ 108
5.2.1 Sociodemographic characteristics of the groups ........ 108
5.2.2 Overall effects of tES on foreign vocabulary learning ........ 109
5.2.3 Effects of other variables on learning performance ........ 111
5.2.4 Adverse effects ........ 111

5.3 Study III ... 112

5.3.1 Sociodemographic characteristics ... 112
5.3.2 Linguistic profile: LEAP-Q ... 113
5.3.3 Effects of tRNS on verbal fluency and SCWT test ... 114
5.3.4 Mediation analysis ... 117
5.3.5 Adverse effects ... 117

**6 Discussion ... 121**

6.1 Effects of tES on second/foreign-language learning processes ... 121

6.2 Effects of tES over time: possible long-term effects ... 123

6.3 tES effects on verbal fluency tasks in multilingual healthy adults ... 127

6.4 The importance of proper set-up: the need for the establishment of common or standardized protocols in tES and (foreign) language learning processes studies ... 128

6.5 Influence of other variables on the effects of tES on second/foreign-language learning processes and verbal fluency ... 130

6.6 Limitations and future lines ... 136

**7 Conclusions ... 141**

7.1 Conclusions ... 141

7.2 Conclusiones ... 143

**8 References ... 147**

**9 Supplementary material ... 173**

# Foreword

The present thesis has been presented to obtain the degree of Doctor of Psychology by the University of Deusto and is the result of three studies conducted in the Neuropsychology of Severe Mental Condition research group, at the Department of Psychology, Faculty of Health Sciences, University of Deusto. In study I, a systematic review and meta-analysis of the effectiveness of transcranial electrical stimulation techniques on second and foreign language learning enhancement in healthy adults was performed; in study II, the comparison and effects of transcranial electrical stimulation techniques on foreign vocabulary learning was conducted; and in study III, the effectiveness of transcranial random noise stimulation on verbal fluency enhancement was analysed in multilingual young healthy adults.

## Study I

Effects of transcranial electrical stimulation techniques on second and foreign language learning enhancement in healthy adults: A systematic review and meta-analysis. Published in: Neuropsychologia, 160, 107985. https://doi.org/10.1016/j.neuropsychologia.2021.107985

## Study II

Effects of transcranial electrical stimulation techniques on foreign vocabulary learning. Published in: Behavioural Brain Research, 438, 114165. https://doi.org/10.1016/j.bbr.2022.114165

## Study III

Enhancement of Phonemic (but not Semantic) Verbal Fluency in Multilingual Young Adults by Transcranial Random Noise Stimulation. (Under review).

# Glossary of Abbreviations

CI = Confidence Interval

DLPFC = Dorsolateral prefrontal cortex

GABA= γ-aminobutyric acid

HD-tDCS= High Definition Transcraneal Direct Current Stimulation

IFG = Inferior frontal gyrus

L-DLPFC = Left dorsolateral prefrontal cortex

L-IFG = Left inferior frontal gyrus

L-PFC = Left prefrontal cortex

NIBS= Non-invasive brain stimulation

NMDA= N-methyl-D-aspartate

PRISMA= Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PROSPERO= Prospective International Registry of Systematic Reviews

pSTG = Posterior superior frontal gyrus

Q= Cochrane's Q test

rSO = Right supraorbital area

SD= Standard Deviation

seTE = Standard Error of Treatment Estimate (standard error of the effect size)

SMD= Standardized Mean Difference

TE = Estimate of treatment effect (Hedges' g; effect size)

tES= Transcraneal Electrical Stimulation

tDCS= Transcraneal Direct Current Stimulation

TMS = Transcranial magnetic stimulation

tRNS= Transcraneal Random Noise Stimulation

tACS= Transcraneal Alternating Current Stimulation

VF= Verbal Fluency

# Glossary of Tables

**Table 1.** Formulas for estimating effect sizes according to the experimental design and data available of each study.

**Table 2.** Inclusion and exclusion criteria of study II and study III.

**Table 3.** Summary of the reviewed studies with sham condition in studying the effects of tES on language learning.

**Table 4.** All 16 estimated effect sizes with 95% CI and percentage weight.

**Table 5.** Summary of effects sizes of each area.

**Table 6.** Results of moderator analyses.

**Table 7.** Baseline demographic characteristics of participants according to the assigned group condition.

**Table 8.** Differences in the number of correct English words (marginal means) remembered and learned by the participants in the first learning session (single stimulation session) and at follow-up (two weeks later).

**Table 9.** Results of pairwise comparisons of all the groups on the follow-up.

**Table 10.** Side effects experienced and reported by participants from active and sham stimulation groups.

**Table 11.** Baseline demographic characteristics of participants according to the assigned group (stimulation or placebo).

**Table 12.** Language profile of the participants (scores obtained from the LEAP-Q).

**Table 13.** Participants' verbal fluency raw scores at baseline, online and offline assessment.

**Table 14.** ANCOVA of the verbal fluency scores obtained by the participants under stimulation or sham (online) and after stimulation (offline) controlling for baseline verbal fluency performance.

**Table 15.** Side effects experienced and reported by participants from tRNS and sham groups.

# Glossary of Figures

**Figure 1.** Example of a non-invasive electrical current device from the 19th century, called “The McIntosh Physician's Faradic Battery”. The battery was inside the wooden box.

**Figure 2.** Illustration of an example of a standard tDCS montage (A) and HD-tDCS (B) set-up example.

**Figure 3.** tDCS electrical currents and mechanisms of action.

**Figure 4.** Examples of stimulation waveforms for the three different types of tES

**Figure 5.** Pitfalls to consider when interpreting the evidence on the effects of tES on foreign language learning processes.

**Figure 6.** PRISMA summary of identified studies and included in the review.

**Figure 7.** Methodological quality and risk of bias assessment of the studies (Cochrane risk of bias tool 2.0 representation with robvis risk-of-bias VSualization tool) (McGuinness & Higgins, 2020; Sterne et al., 2019).

**Figure 8.** An example of each phase of the foreign vocabulary-learning paradigm.

**Figure 9.** Electrode placement for stimulation (tDCS, tRNS, combined tDCS-tRNS stimulation).

**Figure 10.** Experimental procedure.

**Figure 11.** Electrode placement for the stimulation condition of the study (tRNS).

**Figure 12.** General procedure of the study.

**Figure 13.** Overall learning (accuracy) effect sizes of all the included studies. Response times of participants during the learning tasks.

**Figure 14.** Response times of participants during the learning tasks.

**Figure 15.** Follow up of tES effects one week after receiving the stimulation.

**Figure 16.** Funnel plots that show publication bias for: (1) accuracy measure of the studies; (2) response time’s measures of the trials and (3) follow up measures.

# I. Abstract

# 1 Abstract

## 1.1 Abstract

Transcranial electrical stimulation (tES) is a type of non-invasive brain stimulation (NIBS) technique that modulates neuronal activity through the application of a weak electrical current. In recent years, its application has increased significantly, and it has been used to enhance different cognitive domains such as language in healthy adults. Specifically, numerous studies have been conducted on the effects of tES on different language skills (e.g., verbal fluency, picture naming, word reading) in healthy samples. However, there has been little research conducted to date on the effects of tES on the processes involved in foreign or second language learning and the reported results remain unclear. Likewise, the use of a single type of tES and a default electrode placement is common in language studies, when other techniques and electrode montages, scarcely investigated in language, are available.

The present thesis is composed by three scientific contributions. The *first study* quantified the effects of tES on foreign language learning processes (non-words, artificial grammar, and foreign languages) through a systematic review and meta-analysis. The *second study* compared the effects of three different types of tES and analysed whether tES enhances foreign language learning processes. And the *third study* aimed to explore the effects of transcranial random noise stimulation (tRNS) on verbal fluency in healthy multilingual individuals (in three different languages: Spanish, Basque and English).

Results in *study I* showed that tES had a moderate immediate enhancing effect on overall language learning, but that these were not maintained in the long-term. Additionally, the meta-analysis reported that the enhancing tES effects were significantly moderated by years of education. In *study II* a significantly higher learning accuracy was observed after tRNS compared to sham and the other types of tES, but only after two weeks of stimulation, with no difference observed between the stimulation techniques immediately. In *study III* results revealed a significantly better performance by participants who received tRNS in the phonemic verbal fluency tasks in Spanish and English. However, no differences were found between conditions in the verbal fluency tasks in Basque.

In conclusion, findings suggest that tES seems to enhance the mechanisms involved in foreign language learning and facilitate language skills such as verbal fluency in multilingual people. It has also been found that, among the different tES, tRNS could be useful for enhancing the processes involved in foreign language vocabulary learning, and that, applied to the left prefrontal cortex, it could help to improve phonemic fluency, although not semantic fluency, in healthy multilingual adults. Overall, these results provide evidence-based data on the potential of tES applied in language learning processes in healthy populations, but also indicate the great need for further research to understand the scope and impact of these techniques in foreign language learning processes.

*Keywords*: non-invasive brain stimulation (NIBS), transcranial electrical stimulation (tES), tDCS, tRNS, foreign language learning, verbal fluency, bilingualism.

## 1.2 Resumen

La estimulación eléctrica transcraneal (tES) es un tipo de técnica de estimulación cerebral no invasiva (NIBS) que modula la actividad neuronal mediante la aplicación de una corriente eléctrica débil. En los últimos años, su aplicación ha aumentado significativamente, y se ha utilizado para mejorar diferentes dominios cognitivos como el lenguaje en adultos sanos. En concreto, se han realizado numerosos estudios sobre los efectos de la tES en diferentes habilidades lingüísticas (por ejemplo, fluidez verbal, denominación de imágenes, lectura de palabras) en muestras sanas. Sin embargo, hasta la fecha se han llevado a cabo pocas investigaciones sobre los efectos de la tES en los procesos implicados en el aprendizaje otros idiomas, y los resultados siguen sin estar claros. Asimismo, el uso de un único tipo de tES y un solo montaje de electrodos es habitual en los estudios sobre el lenguaje, cuando se dispone de otras técnicas y montajes de electrodos, escasamente investigados en el lenguaje.

La presente tesis se compone de tres contribuciones científicas. El *primer estudio* cuantificó los efectos de la tES en los procesos de aprendizaje de otros idiomas (no-palabras, gramática artificial y lenguas extranjeras) mediante una revisión sistemática y un meta-análisis. El *segundo estudio* comparó los efectos de tres tipos diferentes de tES y analizó si la tES mejora los procesos de aprendizaje de otros idiomas. Y el *tercer estudio* pretendía explorar los efectos de la estimulación transcraneal de ruido aleatorio (tRNS) sobre la fluidez verbal en individuos multilingües sanos (en tres idiomas diferentes: español, euskera e inglés).

Los resultados del *estudio I* mostraron que la tES tenía un efecto moderado de mejora inmediata en el aprendizaje general de idiomas, pero que no se mantenía a largo plazo. Además, el metaanálisis informó de que los efectos de mejora de la tES estaban moderados significativamente por los años de educación. En el *estudio II* se observó una precisión de aprendizaje significativamente mayor tras la aplicación de tRNS en comparación con el placebo y los otros tipos de tES, pero sólo tras dos semanas de estimulación; sin que se observaran diferencias entre las técnicas de estimulación de forma inmediata. En el *estudio III* los resultados revelaron un rendimiento notablemente mejor por parte de los participantes que recibieron tRNS en las tareas de fluidez verbal fonémica en español e inglés. Sin embargo, no se encontraron diferencias entre las condiciones en las tareas de fluidez verbal en euskera.

En conclusión, los resultados sugieren que la tES parece potenciar los mecanismos implicados en el aprendizaje de otros idiomas y facilitar habilidades lingüísticas como la fluidez verbal en personas multilingües. También se ha descubierto que, entre los diferentes tipos de tES, la tRNS podría ser útil para potenciar los procesos implicados en el aprendizaje de vocabulario en otros idiomas y que, aplicado al córtex prefrontal izquierdo, podría ayudar a mejorar la fluidez fonémica, aunque no la semántica, en adultos multilingües sanos. En conjunto, estos resultados aportan datos basados en la evidencia sobre el potencial de la tES aplicada en procesos de aprendizaje de idiomas en poblaciones sanas, pero también indican la gran necesidad de seguir investigando para comprender el alcance y el impacto de estas técnicas en los procesos de aprendizaje de otras lenguas.

*Palabras clave:* estimulación cerebral no invasiva (NIBS), estimulación eléctrica transcraneal (tES), tDCS, tRNS, aprendizaje de otros idiomas, fluidez verbal, bilingüismo.

# II. Introduction

# 2 Introduction

## 2.1 General framework: Use of techniques in the study of cognition

Throughout the history of the neuroscience research, numerous techniques have been developed and implemented. Specifically, in the field of cognitive neuroscience, techniques such as magnetic resonance imaging (MRI) or deep brain stimulation (DBS) have been and continue to be widely used for cognitive function research. Regarding DBS, it has proven to be very useful in understanding the functioning of the brain. In addition, it has brought remarkable benefits in various neuropsychiatric and neurological diseases, improving physical symptoms of the disease, and may have a positive impact on different cognitive abilities (Hescham et al., 2020). However, DBS is invasive and an option that tends to be chosen in very specific cases.

Over time, non-invasive brain stimulation (NIBS) methods have been developed as an alternative. These are a set of techniques that, through different methods (e.g., magnetic fields, electricity), allow modulation of brain activity in a non-invasive manner. The development of these techniques has allowed the creation of a wide field of study with multiple possibilities. These techniques make it possible to study different cognitive processes without the need for any lesion or surgery. Thus, they allow a more widespread use in clinical and research, both for patients and for people without neuropsychiatric or neurological pathologies (Miniussi and Ruzzoli, 2013).

## 2.2 Non-invasive brain stimulation (NIBS): A Brief Overview

Non-invasive brain stimulation (NIBS) techniques allow to modulate cortical excitability in a safe and non-invasive way without the need for surgery (unlike deep brain stimulation), both in people with neurological or psychiatric disorders and in the healthy brain (Polanía et al., 2018). Although NIBS have been used throughout the history of neuroscience to further investigate the brain and find treatments for different diseases; in the past two decades their application and study has significantly increased in human neuroscience research. Nowadays, in addition to being further developed and improved for the treatment of a wide range of neurological and psychiatric conditions (e.g., Parkinson's disease, schizophrenia, major depression, etc.), NIBS are also being used for the enhancement and research of several cognitive domains and processes in healthy populations.

The most used types of NIBS are the transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES). TMS allows the modulation of neuronal activity through magnetic field pulses (Barker et al., 1985; Hallett, 2000). This technique has been widely used since the 1980s (Barker et al., 1985) and continues to be used in research and in the therapeutic environment, with a large corpus of relevant and up-to-date scientific literature (Lorentzen et al., 2022; Valiengo et al., 2022). Nevertheless, due to the advantages of tES (e.g., inexpensiveness, ease of transport and administration) and the wide range of questions to be investigated on its effects, scope and administration, the focus of this thesis will be on tES applied to healthy population.

### 2.3 Transcranial electrical stimulation (tES)

This technique modulates neuronal activity through the application of a low-intensity electrical current by a battery driven stimulator (Fertonani and Miniussi, 2017; Paulus, 2011).

The use of electricity as a tool for the study and treatment of the brain is nothing new. For centuries, human beings have applied electricity for therapeutic purposes, using electricity of animal origin in its beginnings. The earliest reported evidence comes from ancient Greece where philosophers Aristotle and Plato described the use of electricity from torpedo fish for healing purposes (Harris, 1908; Tsoucalas and

Sgantzos, 2016). Also, more reported evidence of the use of animal-source electricity as a healing method can be found throughout history in different parts of the world (Sarmiento et al., 2016). It was centuries later, thanks to the development of technology during the 18th century, when mechanical devices that allowed the application of a constant and more controllable electric current were developed. However, the rise of interest in brain stimulation research was during the 19th and 20th centuries, when several studies focused on the treatment of psychiatric illnesses through electrical brain stimulation were developed (Moreno-Duarte et al., 2014). One of the most famous treatments was electroconvulsive therapy (ECT), applied from the late 1930s onwards, which employed an intense electrical current with significant side effects (Sackeim, 2017). At the same time, throughout the 20th century, interest in the research and use of a weak electrical current as an alternative to ECT increased (Moreno-Duarte et al., 2014; Nitsche and Paulus, 2000), giving rise to the various methods of tES that we have today.

**Figure 1.**

*Example of a non-invasive electrical current device from the 19th century, called "The McIntosh Physician's Faradic Battery". The battery was inside the wooden box.*

*Note:* This illustration was depicted in an 1888 medicine catalogue (Noyes Bros. & Cutler), but the image was retrieved from Wexler, 2017.

In recent years, tES has regained significant research interest for the treatment of symptoms of several diseases and the improvement of cognition in healthy people. Different tES types can be distinguished: transcranial direct current stimulation (tDCS), transcranial random noise stimulation (tRNS), and transcranial alternating current stimulation (tACS).

### *2.3.1 Transcranial Direct Current Stimulation (tDCS)*

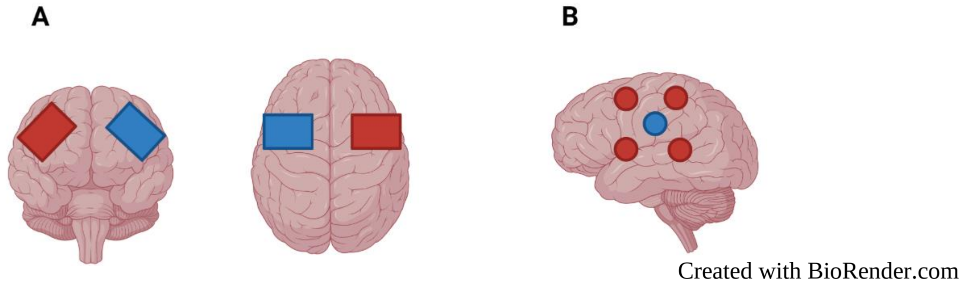
Transcranial direct current stimulation (tDCS) is the most used and studied type of tES. This technique allows to modulate neuronal activity through a weak direct current (usually between 1 and 2 mA) delivered to the scalp via two electrodes, inducing lengthy functional after-effects in the brain, depending on the parameters of stimulation (Monti et al., 2013; Nitsche and Paulus, 2000; Sparing et al., 2008; Woods et al., 2016). These electrodes can be applied in saline-soaked sponges or rubber electrodes with conductive gel (DaSilva et al., 2011; Medeiros et al., 2012; Nitsche and Paulus, 2000).

During tDCS stimulation, the direct current emitted flows through the head from one electrode to another, generating a circuit. Each electrode has a different function: anodal (target electrode) and cathodal (reference electrode). The anodal current (atDCS) is associated with neuronal excitability, whereas the cathodal is related to the inhibition of neuronal activity (Nitsche et al., 2008; Reed and Kadosh, 2018; Thair et al., 2017) Traditionally, the tDCS is applied by using a "bilateral" or "bihemispheric" montage, that is, the anodal electrode is usually placed on one of the hemispheres, while the cathodal electrode is placed on the other equivalent side of the brain or extracephalically, such as on the shoulder.

Although tDCS has proven to be an effective and safe tool for the modulation of cortical excitability (Bikson et al., 2016; Nitsche and Paulus, 2000; Paulus, 2011), its traditional bilateral setup utilizing the conventional size of sponges (5x7 cm) presents some limitations, such as the focality of the emitted current (Moreno-Duarte et al., 2014; Nitsche et al., 2007). Therefore, methods to further focus the stimulation have been proposed. One of the main methods is the so-called high definition tDCS (HD-tDCS), in which electrodes are used on smaller sponges placed in a 4 x 1 ring setup, focusing more accurately on the target brain area (Nikolin et al., 2015; Parlikar et al., 2021; Villamar et al., 2013) (see Figure 2 for details). However, although some studies of the HD-tDCS technique report some advantages (Alam et al., 2016), similar results to conventional tDCS are still observed (Müller et al., 2022; Ostrowski et al., 2022). Therefore, it could be hypothesized that what will determine the immediate and after effects of tDCS depends not only on the stimulation technique per se, but also on several highly relevant factors such as the object of study and stimulated area, where the reference electrode is placed, the intensity (mA), density and duration of the stimulation, whether it is applied while performing the task (online stimulation) or while it is not being performed (offline stimulation), among other variables (Thair et al., 2017).

**Figure 2**

*Illustration of an example of a standard tDCS montage (A) and HD-tDCS (B) set-up example.*



#### 2.3.1.1 Proposed tDCS mechanisms of action

While tDCS has been and continues to be the most widely used type of tES, knowledge about the underlying mechanisms of action of its effects on cognition and behaviour, both immediate and after stimulation, is limited. Nevertheless, several studies have proposed possible basic characteristics of the mechanisms of action of tDCS.

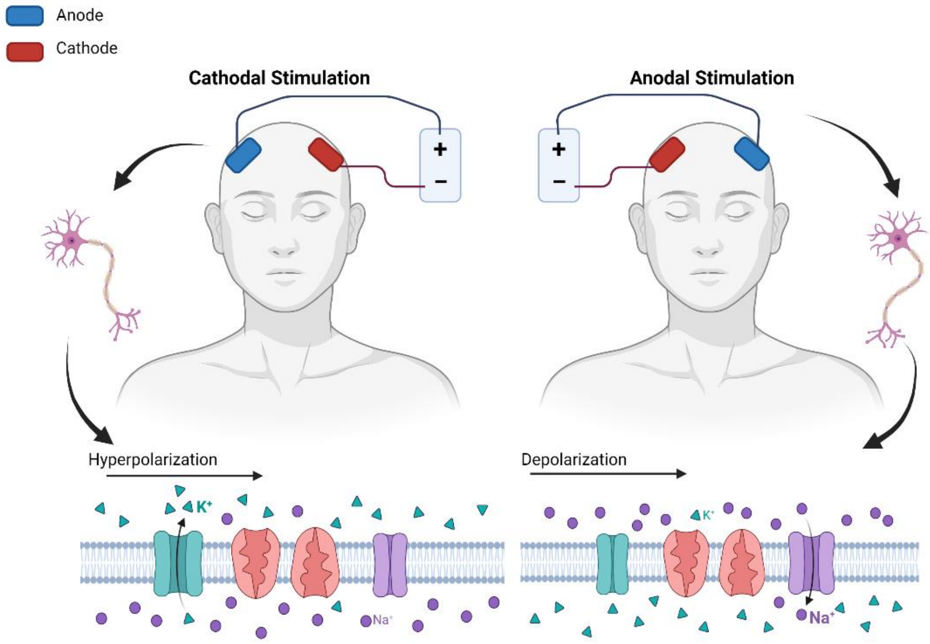
Numerous studies have reported that tDCS acts by increasing glutamate and glutamine and brain-derived neurotrophic factor concentrations (Fritsch et al., 2010; Hunter et al., 2015), and decreasing γ-aminobutyric acid (GABA) concentrations (Bachtiar et al., 2015; Reed and Kadosh, 2018; Stagg and Nitsche, 2011). It is also important to highlight the role of N-methyl-D-aspartate (NMDA) receptors in the short- and long-term effects that may be caused by tDCS, as their blockade interferes with the excitability caused by direct current, thus affecting the possible aftereffects of tDCS (Nitsche et al., 2003).

It is important to note that tDCS does not have a direct impact on the membrane potential, as the electrical power applied in humans is too low to elicit them (1- 2 mA) directly (Chase et al., 2020; Huang et al., 2017; Vöröslakos et al., 2018). Specifically, the low direct current emanating tDCS is considered to be subthreshold, i.e., this technique is capable of modifying neuronal transmembrane potentials and thus altering excitability in specific brain regions (Bikson et al., 2004; Nitsche and Paulus, 2000; Reed and Kadosh, 2018). Therefore, tDCS is considered to have an impact at the level of neural network functioning, critical for cognition and behaviour, such that it affects the probability of action potential generation (Chase et al., 2020; Stagg et al., 2018).

As mentioned above, for the modulation of neuronal excitability with tDCS, two types of currents are applied: anodal and cathodal. The anodal current is associated with depolarization of the neuronal membrane, which causes the neuron to be more likely to fire action potentials, increasing activity. While the cathodal current is related to hyperpolarization of the neuronal membrane, generating less likely to fire action potentials, and decreasing activity (Stagg et al., 2018) (see Figure 3).

**Figure 3**

*tDCS electrical currents and mechanisms of action.*



*Created with BioRender.com*

Finally, it should be noted that direct current always flows from one side to the other, creating a complete circuit. Therefore, it is very important to consider the location of the brain to be stimulated, the power and the orientation of the neuron relative to the electric field to achieve the desired effects (Stagg et al., 2018).

#### 2.3.1.2 Applications in healthy populations

Since its beginnings, tDCS has been mostly investigated and applied for the treatment of neurological and/or psychiatric disorders. Its application to healthy subjects was limited to control groups or to the investigation of its effects in order to improve rehabilitation treatments of the population with neurological and/or psychiatric disorders (Coffman et al., 2014; Kuo et al., 2014). However, in recent years, research on the effects of tDCS on the healthy brain for the improvement of motor skills and cognitive performance has increased significantly. Thus, it is possible to find a wide range of different studies of tDCS in healthy populations, such as sports performance improvement (Jaberzadeh and Zoghi, 2022; Machado et al., 2019; Maudrich et al., 2022), motor skills augmentation (Baharlouei et al., 2020; Hashemirad et al., 2016; Patel et al., 2019) or enhancement of several cognitive domains and abilities (e.g., memory, language, attention, learning, creativity, etc.) (Berryhill and Martin, 2018; Coffman et al., 2014; Dedoncker et al., 2016; Figeys et al., 2021; Lucchiari et al., 2018; Westwood and Romani, 2017).

In the improvement of cognitive processes, the evidence so far reported both beneficial effects (Berryhill and Martin, 2018; Dedoncker et al., 2016; Figeys et al., 2021) and little to no effects (Horvath et al., 2015a; Westwood and Romani, 2018) of tDCS on cognitive function enhancement in healthy samples. These differences in the reported findings have been mainly associated with experimental and technical issues, such as the tDCS protocol parameters (e.g. intensity, electrode positioning, duration, etc.), inter-subject variability, intra-subject reliability, the use of sham-placebo stimulation and blinding, or the application of tDCS in a single session or multiple sessions (more significant and reliable effects have been observed when several tDCS sessions are applied), among others (Horvath et al., 2015b, 2014). However, it should be highlighted that tDCS is now considered a promising tool, used in both clinical and research settings, for the treatment of certain neuropsychiatric disorders and cognitive enhancement.

### *2.3.2 Transcranial Alternating Current Stimulation (tACS)*

Transcranial alternating current stimulation (tACS) allows modulation of brain activity using weak oscillating electric current, by causing effects during stimulation (online effects) and after the end of stimulation (offline effects or after-effects) (Antal and Herrmann, 2016a; Paulus, 2011). In tACS, the type of current emitted by each electrode during stimulation alternates from anodal to cathodal and vice versa (biphasic stimulation). Thus, tACS does not directly affect the membrane potential, but modifies the cortical oscillations (Antal and Herrmann, 2016b; Paulus et al., 2016).

Although this technique has not been used in this thesis, its brief explanation is considered adequate to have greater knowledge and understanding of the general mechanisms of the different types of tES.

#### 2.3.2.1 Proposed tACS mechanisms of action

Although the mechanisms of action of tACS are not entirely clear, possible hypotheses have been proposed. The alternating current of tACS causes the cell bodies and dendrites of cortical neurons to alter membrane potentials toward hyperpolarization or depolarization in an oscillating manner. That is, the main feature of tACS is its ability to increase the probability of action potential generation through continuous oscillations of the weak electric current (Antal and Herrmann, 2016b; Vöröslakos et al., 2018). However, it should be noted that the weak oscillating current emitted is not strong enough to change the number of action potentials. Therefore, when applying tACS it is very important to consider timing (to synchronize with the ongoing brain activity), frequency and location (Krause et al., 2019). The unit for frequency is “hertz” (Hz). The effects of tACS on cognition and motor ability have been investigated through the application of a wide range of different frequencies: the conventional EEG frequencies (0.1–80 Hz) and the so called “ripple” range (80-250 Hz) (Antal and Paulus, 2013; Moliadze et al., 2010).

#### 2.3.2.2 Applications in healthy populations

Similar to tDCS, tACS has been applied in healthy populations to improve performance in different cognitive areas. In particular, it is frequently applied in the study of its effects on the improvement of executive function and learning processes (Lee et al., 2023).

So far, tACS seems to have shown positive results in cognitive function improvement. Specifically, according to data reported by a recent meta-analysis (Lee et al., 2023), the application of online and offline tACS with theta frequency band in the prefrontal or posterior parietal regions improve executive function in healthy participants. Also, another relatively recent systematic review about frequency-specific effects of tACS in healthy populations, indicated that theta-tACS was, indeed, beneficial for different cognitive functions, including working memory, executive functions, and declarative memory (Klink et al., 2020). They also observed beneficial effects of gamma-tACS, but only for auditory and visual perception, and both of gamma- and alpha-tACS for attention (Klink et al., 2020). This demonstrates the great importance of developing protocols with specific timing and electrode setups to take advantage of these techniques.

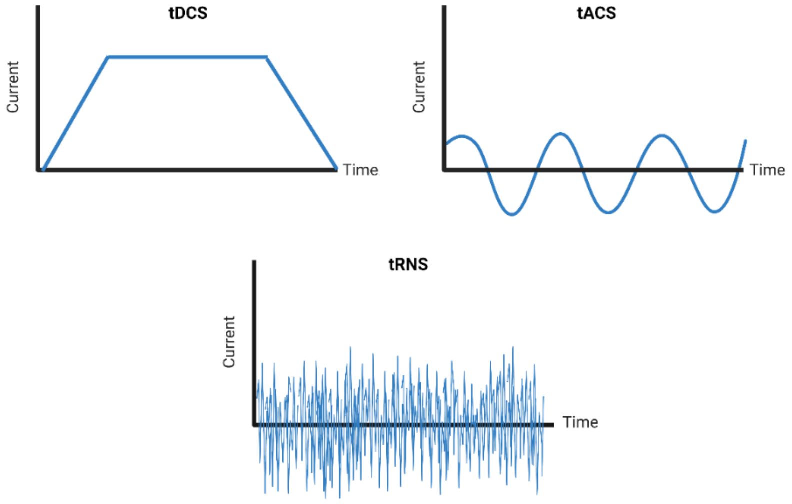
On the other hand, in contrast with tDCS, tACS has not been studied much in the field of language. This can be seen in Lee et al., 2023, where of the 56 studies reviewed since 2010, only two studied the effects of tACS on language processes.

### *2.3.3 Transcranial Random Noise Stimulation (tRNS)*

Transcranial random noise stimulation (tRNS) is a non-invasive brain stimulation technique that delivers an alternating electrical current that changes randomly in intensity and frequency to the scalp via electrodes (Antal and Herrmann, 2016a; Terney et al., 2008). The tRNS frequencies are usually distributed between 0.1 and 640Hz, normally ranging from low (0.1-100Hz) to high (101-640Hz) (see Figure 4) (Fertonani et al., 2011; Terney et al., 2008). Furthermore, a key feature of tRNS is that it is neither anodal nor cathodal, i.e., it is polarity independent (Miniussi and Ruzzoli, 2013). This means that it is possible to use both electrodes for simultaneous stimulation of different cortical areas (van der Groen et al., 2022).

**Figure 4**

*Examples of stimulation waveforms for the three different types of tES.*



*Created with BioRender.com*

tRNS has been shown to modulate brain activity and has been investigated as a potential treatment for a variety of neurological and psychiatric conditions, as well as a tool for cognitive enhancement in healthy populations (van der Groen et al., 2022).

#### 2.3.3.1 Proposed tRNS mechanisms of action

The physiological mechanisms of tRNS are still not fully understood, it is not clarified yet whether tRNS produces an effect by causing plastic changes in the brain (van der Groen et al., 2022) or interferes with current network activity (Antal and Herrmann, 2016b; Miniussi et al., 2013; Paulus, 2011; Paulus et al., 2016). Despite this, different hypotheses on how tRNS could modulate neural activity have been proposed.

Stochastic resonance hypothesis has been proposed to explain tRNS mechanisms of action (van der Groen et al., 2022; van der Groen and Wenderoth, 2016). Stochastic resonance is a nonlinear phenomenon in which the addition of an optimal amount of noise enhances performance, while increasing the amount of noise hinders signal detection or discrimination. (McDonnell and Abbott, 2009; Moss, 2004; Zhou, 2013). Therefore, according to this hypothesis, tRNS could enhance nerve activity by inducing a small amount of random electrical noise in the brain, which could increase the sensitivity of neurons to incoming signals, improving the signal-to-noise ratio in the brain and enhance neural coding (Miniussi et al., 2013; Nazarpoy Shirehjini et al., 2022; van der Groen et al., 2022). Likewise, another proposed mechanism of action closely related to the previous hypothesis is the temporal summation of neuronal activity. That is, tRNS could be triggering the continuous opening of sodium channels and provoke a second sodium influx, resulting in a more significant depolarization of the neuron due to the polarity independence of tRNS (Terney et al., 2008; van der Groen et al., 2022; van der Groen and Wenderoth, 2016).

Neural synchronization is another proposed mechanism of action. It has been hypothesized that tRNS may also increase neural firing synchronization by amplifying the subthreshold oscillatory activity in the brain, which can lead to improved communication between brain regions and improved cognitive processing (Miniussi et al., 2013; Nazarpoy Shirehjini et al., 2022; Potok et al., 2021). Furthermore, it has been hypothesized that tRNS effects could be linked to the repetitious opening of the calcium channel (Chaieb et al., 2015).

On the other hand, several studies have reported that tRNS causes physiological aftereffects that favour increased cortical excitability post-stimulation, especially when the full frequency spectrum is applied (Moret et al., 2019; Terney et al., 2008; van der Groen et al., 2022). Unlike the aftereffects of tDCS that appear to be NMDA-dependent, the aftereffects of tRNS could be associated with modulation of the excitation/inhibition ratio through a decrease in the inhibitory neurotransmitter GABA (Nazarpoy Shirehjini et al., 2022; Sánchez-León et al., 2021). Moreover, it has also been observed that tRNS seems to have greater neuromodulatory influence compared to other tES, which may favour the prolongation of its possible beneficial effects a posteriori on behaviours or cognitive skills (Inukai et al., 2016; Pirulli et al., 2013; van der Groen et al., 2022).

#### 2.3.3.2 Applications in healthy populations

The use of tRNS has gained popularity in the last few years. However, it is still more common to encounter tES studies in healthy populations in which tDCS is used. Nevertheless, it is possible to find studies of tRNS effects on motor (Brancucci et al., 2023; Ho et al., 2015) and cognitive (e.g., executive functions, perception, creativity, etc.) skills (Frank et al., 2018; Herpich et al., 2015; Pasqualotto et al., 2015; Peña et al., 2019).

In particular, there are several studies that compare the effectiveness of tDCS and tRNS on healthy individuals (Ho et al., 2015; Kawakami et al., 2022; Mulquiney et al., 2011; Murphy et al., 2020). So far, evidence has been reported suggesting that tRNS may have a greater neuromodulatory influence, which could in turn have a greater effect on the behaviour or cognitive domain to be enhanced (Lema et al., 2021; Murphy et al., 2020; van der Groen et al., 2022).

Regarding the improvement of cognitive ability in healthy samples, different studies have reported positive effects of tRNS, mostly time after stimulation (aftereffects), rather than on acute stimulation (Brambilla et al., 2021). Specifically, some authors have reported more significant beneficial effects when applying tRNS (Brevet-Aeby et al., 2019; Pasqualotto et al., 2015; Snowball et al., 2013), which has been associated with the proposed mechanisms of action of tRNS (see section 2.2.3.1.).

On the other hand, as with tDCS and tES in general, it is important to consider the stimulation parameters and characteristics of the protocols that studies using tRNS apply (Thair et al., 2017). Likewise, in the case of tRNS, there is still much to be investigated. Overall, however, tRNS is a promising tool for brain modulation and cognitive enhancement, but further research is needed to fully understand its mechanisms of action and its potential clinical applications (Potok et al., 2021).

## 2.4 tES and the study of cognition

In recent years, the use of tES in the investigation of cognitive processes has increased significantly. Nowadays, they are not only used for the development of treatments for psychiatric or neurological pathologies; they are also used as a method for studying cognitive function in healthy populations. Currently, there are many studies on the application of tES in the healthy brain for the improvement of various cognitive domains such as memory, learning, attention, or language, among many others (Dedoncker et al., 2016).

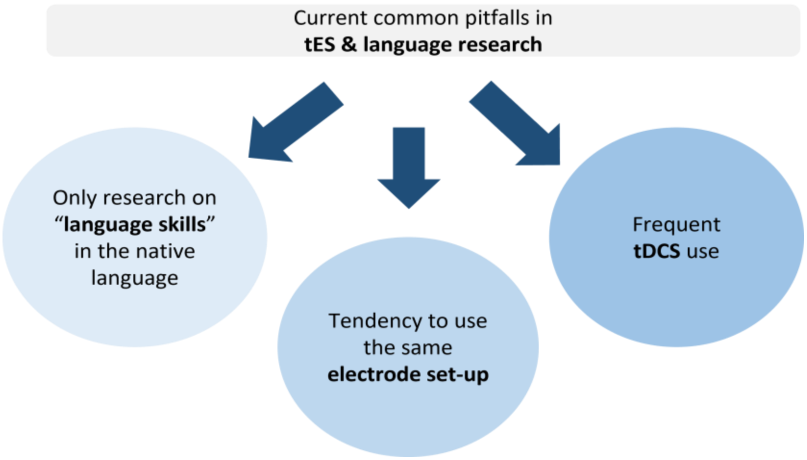
### *2.4.1 tES on language learning studies*

In recent years, several studies have investigated the effects of tES on language among non-clinical samples (Klaus and Schutter, 2018a). In 2008, Flöel and colleagues applied tDCS on a group of healthy participant adults and observed that it could improve non-word learning (Flöel et al., 2008). Since then, several studies have been focused on different language abilities (Livengood et al., 2015), including verbal fluency (Cattaneo et al., 2016, 2011; Monti et al., 2013); naming (Fertonani et al., 2010; Sparing et al., 2008); word retrieval (Fiori et al., 2011); and/or vocabulary (Flöel et al., 2008; Hussey et al., 2015), and shown positive effects on the improvement of different language abilities (e.g., Cattaneo et al., 2011, 2016; Fertonani et al., 2010; Flöel et al., 2008; Hussey et al., 2015; Livengood et al., 2015; Monti et al., 2013; Sparing et al., 2008). Moreover, despite the variability of the results, tES have demonstrated that it could enhance the learning phase of language abilities. This was demonstrated by Simonsmeier and colleagues (2018) in a meta-analysis that included 246 effect sizes from 35 studies on language skills (picture naming, sentence comprehension, vocabulary, fact recall, verbal fluency, and other competence measures) (n = 161) and mathematical skills (mental arithmetic, magnitude comparison, number line estimation and other competence measures) (n = 85). They found evidence of positive effects of neuronal modulation on the learning phase of language and mathematical skills (overall Cohen´s d = 0.343), which showed the beneficial effects of tES on language competence (Simonsmeier et al., 2018).

Nevertheless, there is still little evidence concerning the effects of tES on the processes involved when individuals with no neurological or neuropsychiatric disorders learn new languages, giving rise to various pitfalls or limitations in the interpretation of the related evidence provided so far (see Figure 5). Few studies have investigated the effects of tES on the processes of second and foreign language learning, whether using tasks with non-words (Fiori et al., 2011; Flöel et al., 2008; Meinzer et al., 2014; Xue et al., 2017), artificial grammar (De Vries et al., 2010) or a real foreign language (Fiori et al., 2018; Pasqualotto et al., 2015; Perceval et al., 2017). In addition, previous research on the effects that tES has on the language domain have generally focused on language skills (e.g., picture naming, word reading, verbal fluency, etc.). For example, Price and colleagues (2015) conducted a meta-analysis of studies that assessed the effects of a single session of tDCS on verbal fluency (n = 6) and word learning (n = 2), where they found significant effects of stimulation on language measures in healthy adults (Price et al., 2015). Westwood and Romani (2017) found no significant effects of tDCS, but a small effect on duration and time of stimulation when studying picture naming and word reading (Westwood and Romani, 2017), whereas Klaus & Schutter (2018) reported small but reliable effects of tDCS on picture naming and verbal fluency (Klaus and Schutter, 2018a).

**Figure 5**

*Pitfalls to consider when interpreting the evidence on the effects of tES on foreign language learning processes.*



On the other hand, another common feature in the studies of tES and language is the frequent use of tDCS over other types of tES. This can be observed in a meta-analysis conducted by Klaus and Schutter (2018), who reviewed studies that used non-invasive brain stimulation techniques (TMS, tDCS, tACS, tRNS) 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) (Klaus and Schutter, 2018a). Furthermore, recent studies have also used tDCS in healthy participants for enhancing language skills. After this meta-analysis was published, several studies have been published. Fiori and colleagues (2018) analysed verb-learning processes applying tDCS on healthy participants and using neuroimaging simultaneously. They found behavioural improvements with anodal tDCS and observed a significant decrease in task-related activity in the left inferior frontal gyrus (L-IFG) and its right counterpart (Fiori et al., 2018). Perceval and colleagues (2020) 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 (Perceval et al., 2020). Also, Owusu and Burianová (2020) applied tDCS on healthy adults to study new word recall improvement, and obtained significant positive effects compared to the sham (placebo) group (Owusu and Burianová, 2020). 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. (2015) 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 (Pasqualotto et al., 2015).

Finally, another common characteristic observed in language studies is that certain montages tend to be repeatedly used. The most common ones are those that place the electrodes bilaterally (or bihemispherically), 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.) (Santarnecchi et al., 2015). 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.) (Santarnecchi et al., 2015). 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 (Asbjørnsen and Helland, 2006; Jäncke et al., 1992). Several studies have found a significant association of DL with different language skills, such as language comprehension (Asbjørnsen and Helland, 2006) or speech perception (Hugdahl and Westerhausen, 2016; Thomsen et al., 2004). 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 (Kimura, 1967, 1961; Tanaka et al., 2021). 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 (D’Anselmo et al., 2015; Prete et al., 2018).

Despite this, in recent years, other authors (Klaus and Schutter, 2018b) 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 (Klaus and Schutter, 2018b). 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 (Laakso et al., 2016; Rampersad et al., 2014). 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 (Rampersad et al., 2014). Furthermore, depending on the area stimulated and the targets, a bilateral or unilateral montage may cause different effects (Sehm et al., 2013). However, since then, few studies have used different set-ups in language studies beyond the conventional bilateral set-up described above, generally using the bilateral set-up (Klaus and Schutter, 2018a; Price et al., 2015).

## 2.5 Bilingualism

Nowadays, it is increasingly common to speak more than one language; in fact, in many regions and countries of the world, the use of more than one language in everyday life is widespread (Simons et al., 2022). This increasingly frequent phenomenon is primarily known as bilingualism. However, the concept of bilingualism is complex and there is currently no consensus on its definition (Kremin and Byers-Heinlein, 2021), finding a wide range of definitions in the literature that tends to change depending on the discipline that studies it and the perspective from which it is analysed (e.g., individual, group, language system) (Hoffmann, 1991).

Among the strictest definitions with high standards, it can be found the definition proposed by Bloomfield (1933:56), who indicated that bilingualism is "the native control of two linguistic systems" (cited in Landsberry, 2019). In contrast, other authors proposed much less severe definitions, indicating that a bilingual is a person who "knows" another language, even if he or she has a very basic level of proficiency in it (Diebold, 1964; Macnamara et al., 1968; Valdés and Figueroa, 1994). Between these two positions, there are more moderate perspectives such as the definition proposed by Haugen, 1953:7, who referred to bilingualism as "the point where a speaker can first produce complete meaningful utterances in the other language" or the one proposed by Myers-Scotton (2009:4) who said that "bilingualism is the ability to use two or more languages sufficiently to carry on a limited casual conversation" (cited in Landsberry, 2019).

Currently, a broader definition of bilingualism is used by several researchers that encompasses people with different degrees of language abilities in different domains in both languages, such as "those individuals who need and use two or more languages (or dialects) in their everyday lives" (Grosjean, 2013). These broader definitions enable the development of testing for the assessment of bilingualism in research and the introduction of crucial factors in the measurement of bilingualism, such as the age of acquisition (e.g., early, late), linguistic competence (balanced, unbalanced); language use and exposure, and language proficiency, among several other factors (Hamers and Blanc, 1983; Kremin and Byers-Heinlein, 2021). However, these broader perspectives have been criticized. In particular, they have been accused of being so wide that it ends up conflating the terms bilingualism and multilingualism (De Angelis, 2007).

The term multilingualism is also commonly used to refer to an individual who has obtained the ability to use more than two languages (Clyne, 2017). It is also 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; De Angelis, 2007). Several studies have indicated similarities and differences between the terms “bilingualism” and “multilingualism”. Among the differences observed, multilinguals appear to show greater cognitive flexibility, diverse linguistic strategies, a greater experience in learning a new language when more than one language is previously known and higher degrees of metalinguistic awareness (Aronin and Hufeisen, 2009; Cenoz, 2003; De Angelis, 2007; Hoffmann, 2001; Jessner, 2008; Quinteros Baumgart and Billick, 2018).

In the present thesis, the broad definitions of bilingualism and multilingualism described above have been taken as basis for this thesis, which include those people who know more than one language, since it has several advantages for research (described above) and is coherent with the characteristics of the studies carried out in this thesis (focus on the effects of tES).

### *2.5.1 Bilingualism and cognition*

The relationship between bilingualism and cognition has been extensively studied over time and continues to be the subject of research and debate today. During the early years of the 20th century, bilingualism was believed to be a negative factor for cognitive development (e.g., Smith, 1923), with statements such as "the use of a foreign language in the house is one of the chief factors in producing mental retardation"

(Goodenough, 1926, p. 393; cited in Antoniou, 2019). However, during those years these studies presented numerous methodological problems, such as not considering key variables such as socioeconomic level, age, degree of bilingualism or the frequency of use and exposure to the languages, among many others (Antoniou, 2019; Cenoz, 2008). Late in the 20th and early 21st century and using more rigorous methodology and protocols, new studies did report benefits of bilingualism on cognition.

Currently, it has been reported that being bilingual can favour different cognitive skills (Marian and Shook, 2012). Specifically, the research conducted so far suggests that being bilingual seems to favour executive control, cognitive flexibility and problem solving, as bilinguals or multilinguals are continuously selecting the adequate language for the demands of their environment (Bialystok et al., 2008; Bialystok and Viswanathan, 2009; Hernández et al., 2010; Li et al., 2023). In addition, another aspect that seems to be increased is the metalinguistic awareness of bilinguals compared to monolinguals (Roehr-Brackin, 2018).

Lastly, other studies have shown that learning other languages also has health benefits against neurological diseases, such as the delay of the onset of dementia symptoms (Bialystok et al., 2012; Schweizer et al., 2012). In addition, neuroimaging studies have reported an increase in the volume and thickness of cortical and subcortical brain areas (hippocampus and cerebral cortex), as well as strengthened neural connections while learning a foreign language (Breitenstein et al., 2005; Mårtensson et al., 2012).

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 (Ardila, 2012; Bialystok, 2009; Portocarrero et al., 2007), although this last point is also being debated (see meta-analytical review of Bylund et al., 2022).

### *2.5.2 Bilingualism and verbal fluency*

Verbal fluency is the ease at which a person is able to produce words. It is an ability that requires from motor skills for word articulation to multiple cognitive processes (e.g., working memory, executive control, etc.) (Shao et al., 2014; Troyer et al., 1997). For this reason, in neuropsychology, verbal fluency is frequently assessed to obtain information about an individual's cognitive functioning (Sutin et al., 2019). Verbal fluency tests are divided into a semantic task and a phonemic task (Lezak et al., 2012). The first task consists of producing for one minute the most words within a semantic category, while the phonemic fluency task consists of saying for one minute all words beginning with the given letter (letter fluency) (Shao et al., 2014).

Several studies use phonemic and semantic verbal fluency tests as a measure to examine language processes and executive functions in bilinguals (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 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 L-IFG (Costafreda et al., 2006; Grogan et al., 2009; Katzev et al., 2013; Luo et al., 2010).

However, when studying the performance of bilinguals in verbal fluency tasks, the results obtained are contradictory, sustaining the debate surrounding the advantage or disadvantage of bilingualism (and 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 or multilinguals compared to monolinguals in verbal fluency tasks (especially in semantic verbal fluency). It has been 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 and 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., 2004; Bialystok and Viswanathan, 2009; 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).

### *2.5.3 tES on bilingualism and verbal fluency studies*

Several studies suggest that tES can be a useful tool for investigating verbal fluency and bilingualism, reporting that these techniques may have potential for enhancing different language processes (Klaus and Schutter, 2018a; Tong et al., 2020; Vaughn et al., 2021). However, at the time this thesis was written, no studies on tES and verbal fluency have investigated the effects of, specifically, 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 multilinguals, and that focus on reading or enhancement language switching skills (Bhattacharjee et al., 2020, 2019; 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 when stimulating the left prefrontal (or frontotemporal) brain areas (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). One of the main reasons for the variability in results may be due to the use of different stimulation protocols. For example, in a study by Westwood and Romani (2018), where they summarize stimulation protocols from different verbal fluency studies using tDCS, it can be seen that those stimulating the IFG with anodal tDCS (0.75-2mA, 20 minutes) obtained significant results, unlike the others stimulating other brain areas (Westwood and Romani, 2018). Nevertheless, in the same study, the authors sought to replicate the stimulation parameters, targeting the IFG, but found no stimulation effects (Westwood and Romani, 2018).

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 latter variable, in language studies it is common to place the electrodes bilaterally (two electrodes, one on each cerebral hemisphere) (Santarnecchi et al., 2015). Given this situation, 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, 2018b). 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. (2017) compared the effects of four set-up types (frontal, fronto-temporal, bilateral and unilateral) on verbal fluency in healthy adults using anodal tDCS (2mA current, 20 minutes). 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).

# III. Approach to the present thesis and objectives

# 3 Approach to the present thesis and objectives

This thesis includes three studies that analyse on the one hand, the effectiveness of different electrical stimulation techniques over foreign language learning processes in healthy participants; and on the other hand, the effects of electrical non-invasive stimulation techniques over foreign language learning cognitive processes and verbal fluency performance in multilingual healthy adults. The objectives and hypotheses for each study are described below.

## 3.1 Study I

***"Effects of transcranial electrical stimulation techniques (tES) on second and foreign language learning enhancement in healthy adults: A systematic review and meta-analysis".***

*Background*

tES techniques have been applied to enhance several cognitive domains including language in healthy adults. While different reviews and meta-analysis have been conducted on the effects of tES on various language production skills (picture naming, verbal fluency, word reading), there has been little research done to date on the effects of tES in foreign language learning processes.

*Objectives*

- This systematic review and meta-analysis aimed to study and quantify the effects of tES on foreign language learning processes, focusing on accuracy, response times and 1-week follow-up effects, if reported by the studies, in healthy adults.

- The second objective was to analyse whether stimulation has any effect on response times (learning speed) and if so, whether the benefits of tES persist over time (one week after the stimulation took place).

*Hypothesis*

- Non-invasive brain stimulation techniques could favour foreign language learning or second language production processes.
- Age and/or years of education could be a relevant factor in the effectiveness of the stimulation in foreign language processes enhancement.

## 3.2 Study II

***"Effects of transcranial electrical stimulation techniques on foreign vocabulary learning"***

*Background*

tES in healthy populations has been associated with language learning and production enhancement. However, research on the effects of tES on foreign language learning processes is limited and findings remains unclear.

*Objectives*

- The main objective of this study was to investigate whether tES enhances foreign language learning processes when applied using an unihemispheric electrode montage over the left hemisphere, targeting the inferior frontal gyrus and superior temporal gyrus, area of stimulation influence over Wernicke's region.

- The second goal was to investigate and compare the effectiveness of three different tES techniques (transcranial direct current stimulation, transcranial random noise stimulation and a combination of both) on healthy adults for improving foreign vocabulary learning.
- The third objective was to investigate the long-term effects of a single stimulation session on learning, conducting a two-week follow-up.

*Hypothesis*

- Transcranial electrical stimulation would improve foreign vocabulary learning when compared to sham stimulation.
- Active tES stimulation would lead to a better performance than sham at the follow-up assessment.
- Years of education could influence the participants overall performance when receiving tES.

## 3.3 Study III

### *“Enhancement of Phonemic Verbal Fluency in Multilingual Young Adults by Transcranial Random Noise Stimulation”*

*Background*

Many studies have investigated the effects of transcranial direct current stimulation (tDCS) on verbal fluency tasks in non-clinical populations, focusing on monolingual participants. However, the observed effects on verbal fluency are inconsistent. Furthermore, the effect of other techniques such as transcranial random noise stimulation (tRNS) on improving verbal fluency has not yet been studied in healthy multilingual populations.

*Objectives*

- The main objective of the present study was to analyse 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, by applying tRNS, simultaneously stimulating the L-DLPFC and L-IFG areas.
- The second aim was to study the possible influence of performance in executive functions on the verbal fluency tasks performance after stimulation. To this extent we tested whether performance in the Stroop test could mediate the effect of stimulation on the performance in verbal fluency tasks.

*Hypothesis*

- Transcranial random noise stimulation (tRNS) would improve phonological and semantic verbal fluency tasks in the three languages.
- Executive function performance could be a relevant factor that could influence the effects of tES over verbal fluency performance.

# IV. Methods

# 4 Methods

## 4.1 Study I

### *4.1.1 Inclusion criteria*

This systematic review and meta-analysis included studies that met the following criteria: (1) studies published between 2000 and 2020, (2) use of tES (tDCS, HD-tDCS, tRNS or tACS), (3) studies including a sham condition, (4) studies conducted on healthy adult participants aged between 18 and 70 years old, and (5) studies that investigated the effects of tES on second or foreign language learning (through tasks with non-words, artificial grammar or foreign vocabulary/grammar). Also, the meta-analysis only included trials with the required data to estimate effect sizes (i.e., means, standard deviations, *t* scores or *F*, etc.). Whenever necessary, authors of the original studies were contacted. In accordance with the main objective of this meta-analysis, which was to analyse the effects of tES on language learning, the only selected studies were those that used non-words, foreign vocabulary language-learning or artificial grammar tasks, in a language other than those spoken by participants.

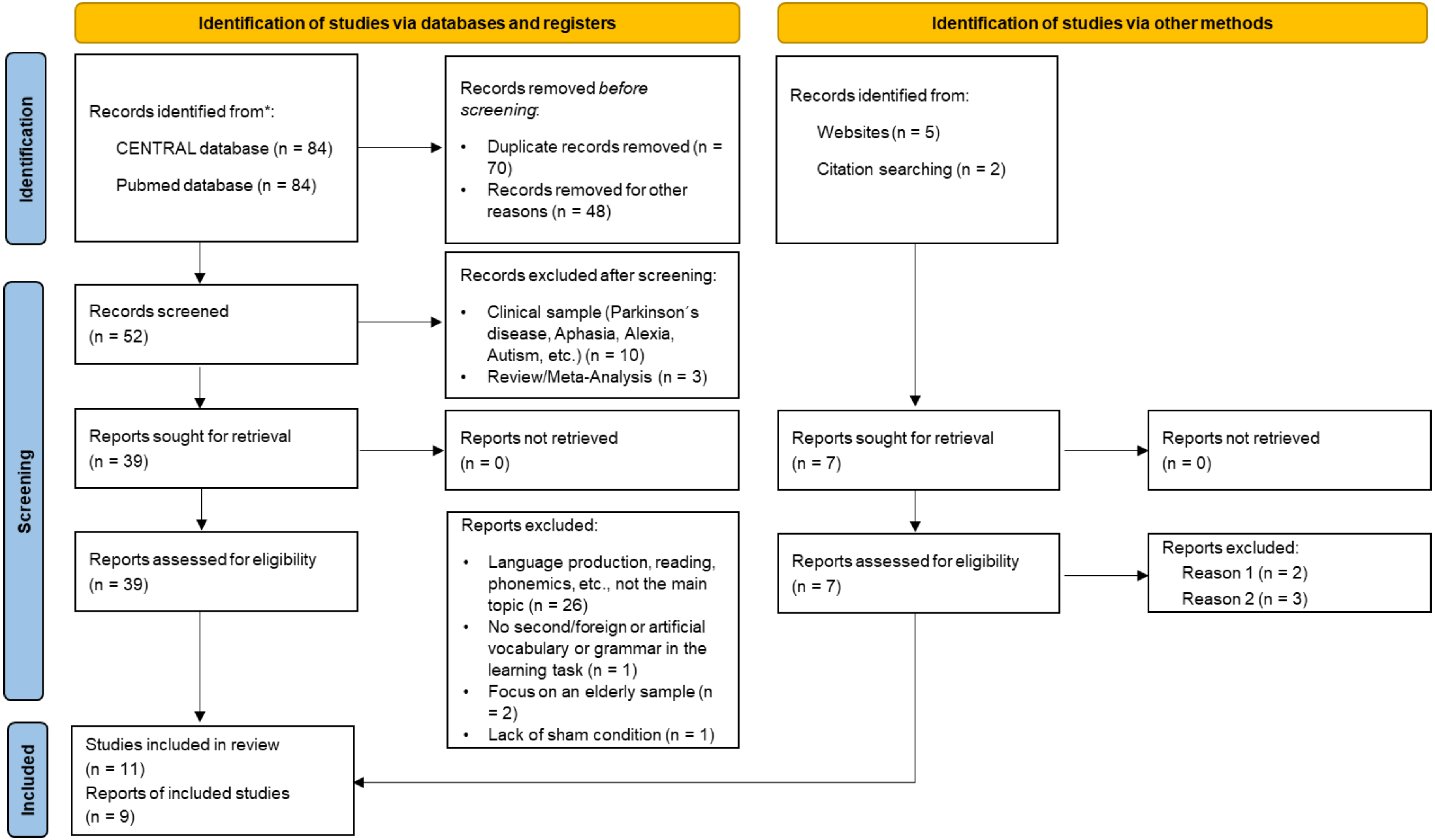
### *4.1.2 Literature search*

For the development of this meta-analysis the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement was followed (Liberati et al., 2009; Page et al., 2021). This systematic review protocol was also registered with the International Prospective Register of Systematic Reviews, PROSPERO (CRD42021234352). Cochrane Central Register of Controlled Trials (CENTRAL), and Pubmed databases (from 2000 to December 2020) were searched using the following search terms: 1) tDCS or tRNS or tACS or transcranial direct current stimulation or transcranial random noise stimulation or transcranial alternating current stimulation; 2) language learning*; 3) foreign language learning or second language learning; 4) new/novel vocabulary learning, and 5) healthy adults or healthy participants*. To carry put a more comprehensive search, the terms were combined as follows: (1) + (2); (1) + (3); (1) + (4); (1) + (2) + (5); (1) + (3) + (5); (1) + (4) + (5); (1) + (2) + (3) + (5). For a better understanding of the search strategy applied, see supplementary material Table S1. For the search, the available filter of year of publication (from 2000 to December 2020) was used. Additionally, we specified the terms to be found in the title, abstract and/or keywords of the studies. A general internet search was also carried out to detect related studies using time filter (from 2000 to December 2020). Following the steps described above in the literature search, two authors independently screened the articles by title, abstract and full-text reading, in accordance with the previously established inclusion and exclusion criteria. Also, each author selected and read the studies that would be eligible for systematic review and meta-analysis. Disagreements were resolved through discussion. If no agreement was reached, a third author (J.P) intervened until mutual consensus was reached.

The results of the first search showed 168 studies from the used databases of which 116 were excluded because they either were duplicate publications (n = 70) or had nothing to do with the topic (n = 46). Fifty-two records were screened, of which 13 were eliminated because they had a clinical population sample, or they were reviews and meta-analyses. Then, the remaining 39 records were retrieved and fully read, including those that investigated the excitatory effects of stimulation techniques during linguistic processes or tested the effects of the stimulation in different language abilities not focusing on second or foreign languages learning (through real or artificial words). Twenty-eight of those studies were excluded due to the following exclusion criteria: (a) they were language production, reading and phonology studies; (b) they made no use of foreign or artificial vocabulary or grammar in the learning task; and (c) they focus only on an elderly sample. Finally, 11 studies were included in the systematic review for qualitative analyses, while nine of the studies were selected for this meta-analysis, including between-participant and within-participant design studies. Figure 6 summarizes the literature search process.

**Figure 6**

*PRISMA summary of identified studies and included in the review.*

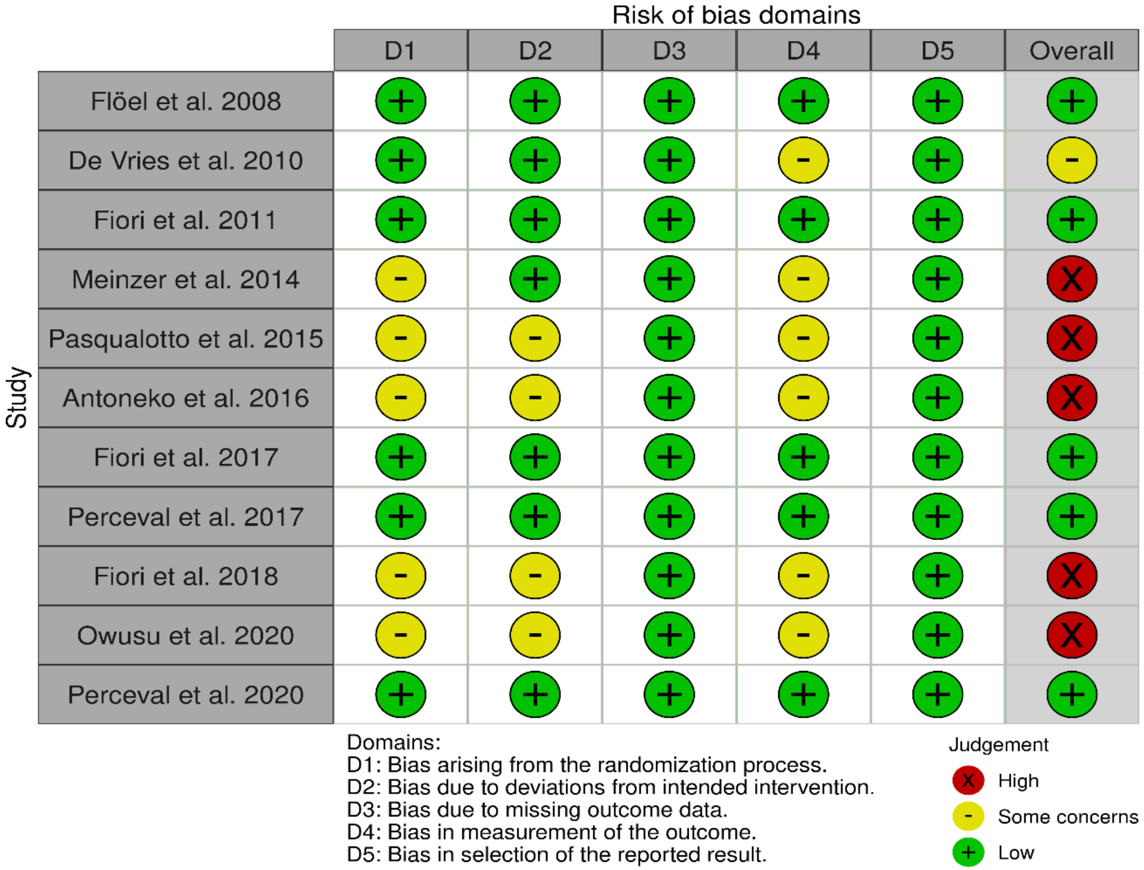


### *4.1.3 Study quality assessment*

The Cochrane risk of bias tool (RoB 2) (Sterne et al., 2019) was used to assess the methodological quality of the trials included in this systematic review and meta-analysis. RoB 2 is structured into five different domains. Within each of these domains there are various questions to assess the level of risk of bias of trials. As a result, they are classified as being of high, medium, or low methodological quality. Two researchers carried out the quality assessment independently, by classifying the risk of bias as being low, high or unclear. The inter-rater agreement for the risk of bias assessment questions from the domains was 86%. Disagreements were resolved by discussion until consensus was reached (see Figure 7 and supplementary material Table S2). In accordance with the RoB2 tool guidelines (Sterne et al., 2019), the overall risk of bias judgment was made on the following criteria: (1) for a *low* overall risk of bias, all domains of the study have to be judged to be at a low risk of bias; (2) as for *some concerns* in overall risk of bias, the study has to have raised some concerns in at least one domain, but not to be at a high risk of bias for any domain; and (3) for a *high* overall risk of bias, the study has to have at least one domain a high risk of bias (or the study has some concerns for multiple domains in a way that substantially lowers confidence in the result). None of the analysed studies were excluded.

**Figure 7**

*Methodological quality and risk of bias assessment of the studies (Cochrane risk of bias tool 2.0 representation with robvis risk-of-bias VSualization tool)* (McGuinness and Higgins, 2020; Sterne et al., 2019).



Risk of bias domains

| Study | D1 | D2 | D3 | D4 | D5 | Overall |
|---|---|---|---|---|---|---|
| Flöel et al. 2008 | + | + | + | + | + | + |
| De Vries et al. 2010 | + | + | + | - | + | - |
| Fiori et al. 2011 | + | + | + | + | + | + |
| Meinzer et al. 2014 | - | + | + | - | + | X |
| Pasqualotto et al. 2015 | - | - | + | - | + | X |
| Antoneko et al. 2016 | - | - | + | - | + | X |
| Fiori et al. 2017 | + | + | + | + | + | + |
| Perceval et al. 2017 | + | + | + | + | + | + |
| Fiori et al. 2018 | - | - | + | - | + | X |
| Owusu et al. 2020 | - | - | + | - | + | X |
| Perceval et al. 2020 | + | + | + | + | + | + |

Domains:
D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended intervention.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement
X High
- Some concerns
+ Low

### *4.1.4. Data extraction*

We calculated all the effect sizes from means, standard deviations (SD), F-scores and t-tests scores for participants' overall learning after the stimulation (accuracy data), response times, and at one-week follow-up if reported by the studies.

The focus was on anodal stimulation applied to similar brain areas by the selected studies according to our main objective. Therefore, if any effects of cathodal stimulation on language learning were shown by a study, they were not reported in our meta-analysis.

Additionally, to ensure an adequate quantitative comparison for the meta-analysis, the effect size of two of the studies (Fiori et al., 2017; Perceval et al., 2020) was not included since the quantitative comparison between groups did not directly address the effects of tES in healthy adults, as previously stated in the inclusion and exclusion criteria above.

### *4.1.5. Statistical analysis*

As has been pointed out in previous reviews on the effects of tES (Westwood and Romani, 2017), numerous studies have employed within-subject designs where they tested the different conditions of stimulation (tES and sham) in the same group of participants. In the present meta-analysis, five within-subject design studies were included that met the set inclusion criteria. However, as indicated by Lakens (2013) or Borenstein and colleagues (2009), among others, it was necessary to perform the effect size calculations in a slightly different way for each type of design to obtain more accurate and comparable effect sizes. Therefore, different formulas were used to calculate the effect sizes for the selected trials.

To estimate the effect sizes of between-participants design studies, the standardized mean difference Cohen´s d formula (Cohen, 1988) was used where the numerator is the difference between the mean of the stimulated group and the mean of the placebo-sham group, and the denominator is the pooled standard deviation. However, when the between-participant design studies only facilitated t-test data, a modified Cohen´s d formula was used (see Table 1).

To estimate the effect sizes of within-participant design studies, a different formula that can be seen in Table 1 was used. In this formula, the numerator is the difference between the mean of the stimulated group and the mean of the placebo-sham group, the denominator is an alternative formula to calculate the standard deviation of the difference scores from the standard deviations of both groups (Cohen, 1988; Lakens, 2013); and *r* is the correlation between tES and sham control scores. However, the studies analysed did not report these correlations, consequently, we set an r of 0.6, based on the correlation score used in the meta-analysis by Westwood and Romani (2017). The calculations were based on numerous results from their previous research (Westwood and Romani, 2017). However, when only *t* values were reported by within-subject design studies, the effect size was estimated with a simpler formula (see Table 1) (Lakens, 2013).

Finally, because of the small sample sizes of the studies included in the meta-analysis, the effect sizes results obtained were corrected by using the small sample size bias adjustment formula, or Hedges´s g (Cumming, 2012).

**Table 1.**

*Formulas for estimating effect sizes according to the experimental design and data available of each study.*

| Study design | Data available | Formula |
|---|---|---|
| Between participants | M, SD, sample | $Cohen\acute{}s\ d = \frac{M_{tES} - M_{Sham}}{\sqrt{\frac{(n_{tES} - 1)SD_{tES} + (n_{sham} - 1)SD_{sham}}{(n_{tES} + n_{sham}) - 2}}}$ |
| | t-Test, sample | $d = t\sqrt{\frac{1}{n_{tES}} + \frac{1}{n_{sham}}}$ |
| Within participants | M, SD, sample | $Cohen\acute{}s\ d_w = \frac{M_{tES} - M_{sham}}{\sqrt{SD_{tES} + SD_{sham} - 2\ x\ r\ x\ SD_{tES}\ x\ SD_{sham}}}\ x\ \sqrt{2\,(1 - r)}$ |
| | t-Test, sample | $d = \frac{t}{\sqrt{n}}$ |
| **Other analyses** | | **Formula** |
| Hedges's g correction | | $Hedges\acute{}s\ g_s = Cohen\acute{}s\ d_s\ x\ \left(1 - \frac{3}{4\,(n_{tES} + n_{sham}) - 9}\right)$ |

Trials with similar experimental procedures (e.g., same current intensity, stimulation to the same brain area, etc.), were included in the review, however, the same true effect size and variation cannot be assumed across all the included studies (fixed-effect model) (Borenstein et al., 2009). Therefore, the random-effects model was used for all analyses, because of the expected heterogeneity. Heterogeneity was reported using Cochran´s Q Test and $I^2$ index, where the $I^2$ index can indicate low (25%), medium (50%), or high (75%) heterogeneity (Huedo-Medina et al., 2006).

Detection of possible outliers was conducted with the *dmetar* package from the RStudio software, using *"find.outliers"* and *"InfluenceAnalysis"* functions. These functions look for outlying values, remove them and recalculate the results; and allow us to estimate various influence diagnostics, respectively (Harrer et al., 2019). We did not remove any effect size as an outlier.

To assess any possible impact of different variables in the selected studies, meta-regression analyses were conducted using a mixed-effects model (Cheung and Vijayakumar, 2016):

$$y_i = \beta_0 + \beta_1 x_1 + u_1 + e_i$$

where $x_i$ is the moderator variable in the *i*th study, $\beta_0$ is the common population effect of the effect size, Var($u_i$) = $\tau^2$ corresponds to the residual heterogeneity after controlling for $x_i$, and $\beta_0$ and $\beta_1$ are the intercept and the regression coefficient, respectively (Cheung and Vijayakumar, 2016). We analysed the possible moderator effects of the mean age of participants, type of study design (between or within participant design), years of formal education of participants, and the number of tES sessions conducted (one or multiple sessions).

Publication bias was assessed using a funnel plot and Egger's test. Publication bias refers to the tendency to publish only studies that have positive and significant results. It is a frequent problem in meta-analyses (Thornton and Lee, 2000).

Additionally, sensitivity analyses were carried out. The analyses were undertaken again using an r of .4 and .8 (Borenstein et al., 2009) for the within-subject design studies that provided the necessary data to estimate the effect size. The purpose was to see if there were any major changes to the results previously obtained. Although the r used in this meta-analysis was based on numerous tES and language studies

(Westwood and Romani, 2017), these studies were focused on picture naming and word reading, and not on foreign language learning processes. The main analyses were also performed excluding the studies with multiple stimulation sessions to identify any changes from previous results.

All the effect size calculations and analyses were conducted using the Practical Meta-Analysis Effect Size Calculator (https://campbellcollaboration.org/), Review Manager (RevMan, Version 5.3), and the *meta, dmetar* and *metafor* packages in RStudio (Version 1.2.5042).

## 4.2 Study II

### *4.2.1 Participants*

Sixty-four volunteers (49 females and 15 males, mean age 28.50 ± 10.76) participated in the study. 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 all right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). 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. The inclusion and exclusion criteria are display in *Table 2*.

**Table 2.**

*Inclusion and exclusion criteria of study II and study III.*

| Inclusion criteria *(Studies II & III)* | Exclusion criteria *(Studies II & III)* |
|---|---|
| • Being male or female (sex). | • Suffering from frequent or severe headaches or migraines. |
| • Being between 18 and 60 years old. | • A history of brain surgery. |
| • Being a native Spanish speaker. | • Being pregnant. |
| • Knowing at least one more language than Spanish (e.g., Basque and or English) | • A history of neurological disorder or injury (brain stroke, severe brain injury, epilepsy, or convulsive seizures). |
| | • Having a metal brain implant. |

The experimental studies conducted in the present thesis (study II and study III) were approved by the Ethics Committee of the University of Deusto (Ref: ETK-40/18-19) and were conducted in accordance with the ethical principles for medical research involving human subjects of the Declaration of Helsinki (World Medical Association, 2013). All participants signed an informed consent document after being informed of the objective of each study, the possible side effects, and benefits of tES, their rights, and the confidentiality and management of data during the study. Participants did not receive any monetary compensation for taking part.

### *4.2.2 Stimulus selection*

*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 (1980) and provided 360 words with their corresponding color images for experimental and clinical use. They analysed 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 S3*), 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) (Moreno-Martínez & Montoro, 2012). 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 (41.83%). Fifty-five other words were added for the recognition part of the paradigm. These words were selected randomly from other non-standardized sources.

*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: 615x458 pixels).

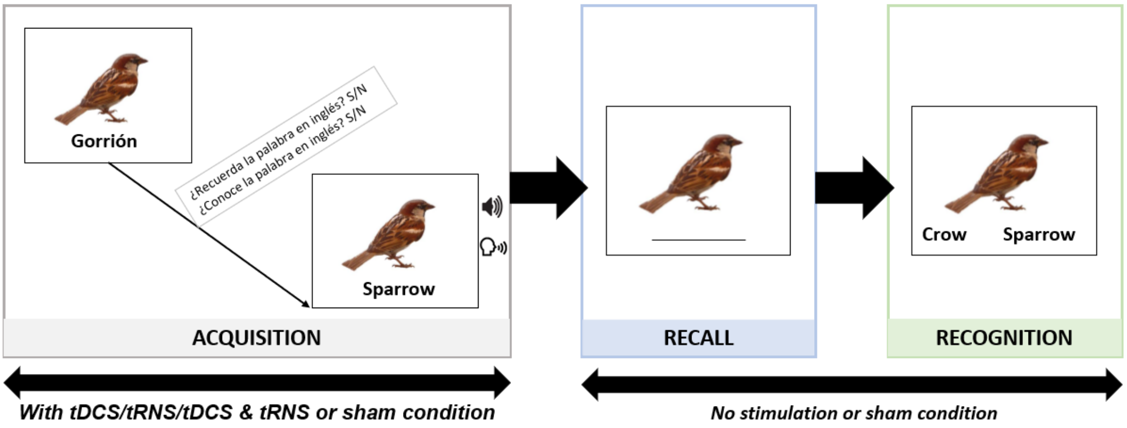
### *4.2.3 Experimental learning paradigm*

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 (see Figure 8) were employed to assess the participant's level of knowledge about the selected terms in English (Spanish word (4 seconds) →

questions (4 seconds) → English word translation (4 seconds) + sound of the word). 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. Finally, in the recognition 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. An example of each phase of the paradigm is shown in Figure 8.

**Figure 8**

*An example of each phase of the foreign vocabulary-learning paradigm.*



*Note*: The participants completed the acquisition, recall and recognition phases in the first session; but recall and recognition parts were implemented two weeks later, with no stimulation.

### *4.2.4 Materials and instruments*

*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).

*The Edinburgh Handedness Inventory.* Handedness was evaluated by the Edinburgh Handedness Inventory (Oldfield, 1971). 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).

### *4.2.5 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 minutes, with additional 30 seconds ramp-up and ramp-down phases. In the sham condition, current was applied using a 30s ramp-up followed 20 min after by a 30s 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 (Trans Cranial Technologies, 2012). The stimulated electric field for each electrode placement can be seen in Figure 9.

*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 1.5mA via two saline-soaked (5 ml approximately per sponge), 8 cm$^2$ circular sponges.

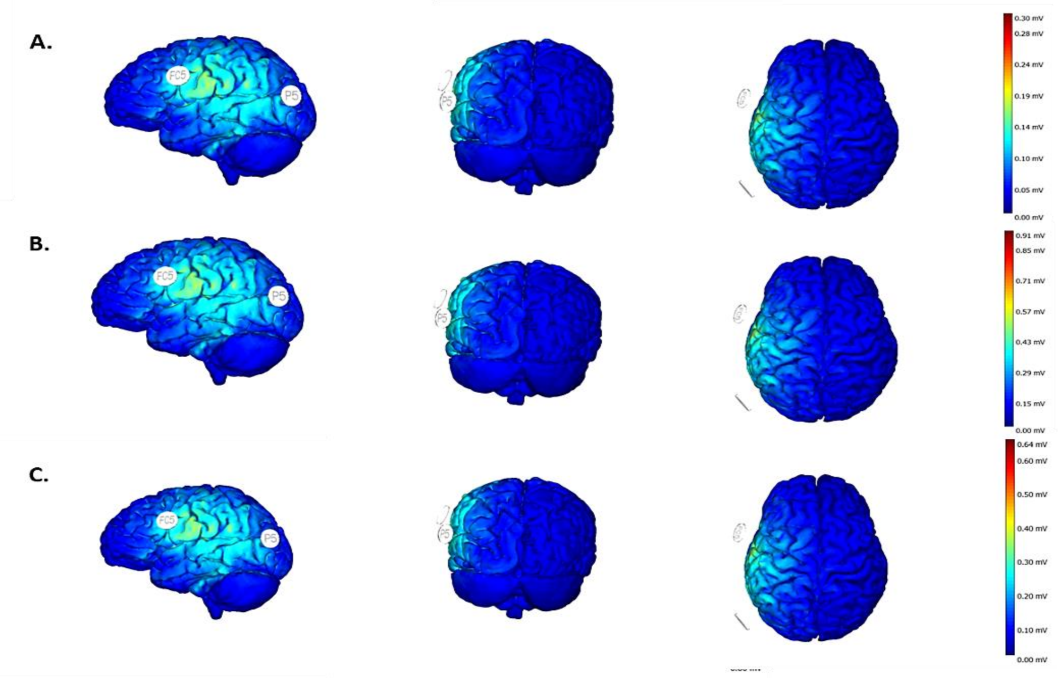
*Transcranial random noise stimulation (tRNS).* In the tRNS group the electrodes were placed over the same areas (P5 and FC5), with 1.5mA current (100–500 Hz). It was applied via two saline-soaked (5 ml approximately per sponge), 8 cm$^2$ circular sponges.

*Combined tDCS-tRNS stimulation*. In this type of stimulation 1mA tDCS with 0.5 mA of tRNS (high-frequency: 100–500 Hz) was applied simultaneously: the anode was placed over the IFG (FC5 according to the 10/20 electrode placement EEG-System) and the cathode over the STG (P5). The current was delivered via two saline-soaked circular sponges of the same size.

*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.

**Figure 9**

*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 (Miranda et al., 2013). A.: tDCS; B.: tRNS; C.: combined tDCS-tRNS.

### *4.2.6 Study design and procedure*

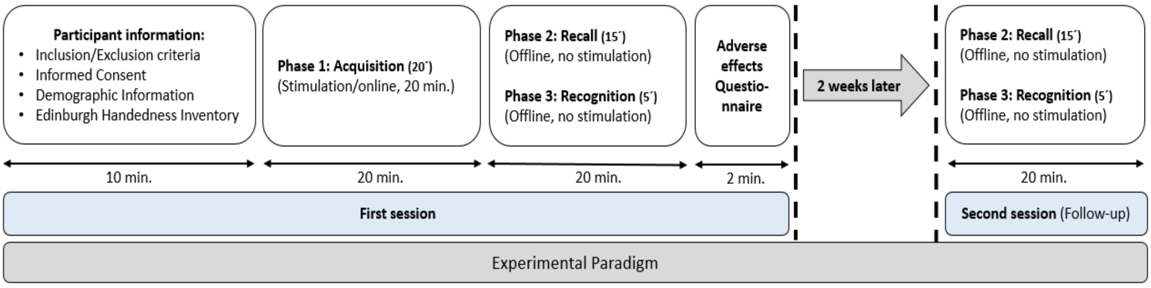
The study had a randomized, sham-controlled, parallel group, double-blind design. The volunteers were randomly allocated to the different condition groups (either tDCS, tRNS, tDCS/tRNS or sham) using a computer-generated randomization (randomizer.org).

All participants were tested individually in two different sessions (see Figure 10). 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. In the 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 minutes, to maximize stimulation effects (Simonsmeier et al., 2018). The stimulation cap was then removed, and they performed the recall and recognition phases without receiving any stimulation.

In the second session, about two weeks later (14.67±1.61 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.

**Figure 10**

*Experimental procedure.*



### 4.2.7 *Statistical analysis*

The statistical analyses were carried out using SPSS version 27 for Windows (IBM Corp, 2020). 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 independently, with the first session stimulation scores and follow-up session scores as dependent variables (for immediate and follow-up stimulation effects comparison), 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 (Hayes, 2018), 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 ($\eta_p^2$) was used to measure effect size in ANCOVA. For the intervals of interpretation of $\eta_p^2$, 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 (Cohen, 1988).

## 4.3 Study III

### *4.3.1 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 probability of error of 0.05 and to achieve an alpha power of 0.95, the program set a minimum sample size of 42 participants. Nevertheless, in the present study it was considered appropriate to increase the sample to achieve a higher 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 same inclusion and exclusion criteria were applied as in study II (see Table 2). Participants did not report any 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, the order of each language acquisition was as follows: Spanish, Basque and English (88, 5%); Spanish, English and Basque (3, 8%); Basque, Spanish, and English (1, 9%) and Spanish and English (5, 8%). The age of acquisition of each language, the subjective proficiency and frequency of use and exposure of the participants to each language was reported. All participants had normal or corrected-to-normal vision.

### *4.3.2 Materials and instruments*

*The Edinburgh Handedness Inventory.* See Study II “materials and instruments” for details.

*The Stroop Colour and Word Test (SCWT).* SCWT is a neuropsychological test, of individual application, widely used for the assessment of different cognitive processes, both in clinical and non-clinical populations (Golden, 2010). In this study, it was used to evaluate the processing speed and cognitive flexibility of the participants. The internal consistency of the overall score was high (Cronbach's alpha = 0.80).

*Verbal fluency tasks.* For verbal fluency assessment, we used the verbal fluency test, divided in 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 = 3), and in three different languages for the multilingual participants (Spanish, Basque and English; n = 47). All phonemic (letters) and semantic (categories) tasks were counterbalanced across participants.

- Phonemic fluency: participants had to produce words starting with a specific letter within one minute. For this task, letters “P”, “M”, “R”, “F”, “A”, “S”, were used for Spanish; “L”, “F”, “A”, “S”; “C”, were used for English; and “E”, “A” and “B” were used for the Basque language. The letters "P", "M", “R”, and “F”, “A”, “S” are frequently used by Spanish speakers. The letters were selected on the basis of their high frequency of use in each language and considering all participants are Spanish-speakers (Casals-Coll et al., 2013; Olabarrieta-Landa, 2017).
- Semantic fluency: For the semantic task, participants had to say within one minute all the possible words that belonged to the given semantic category. In

this case, the categories used for the three languages were animals, professions, and fruits and vegetables.

*Language Experience and Proficiency Questionnaire (LEAP-Q)*. To assess the linguistic profiles of the participants, we used the LEAP-Q in paper-and-pencil format. This self-reported questionnaire is a validated tool that allows the detailed assessment and description of language proficiency, language exposure, language immersion, and language use preference in different contexts, among 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).

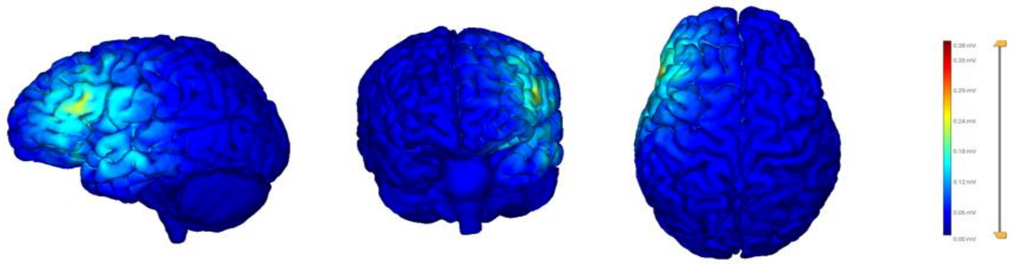
*Adverse Effects Questionnaire*. See Study II "materials and instruments" for details.

### *4.3.3 Electrical stimulation protocol: tRNS*

tRNS was administered through 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 minutes, with additional 30 seconds ramp-up and ramp-down phases. The electrodes were placed over the L-DPFC and L-IFG areas (F3 and FT7-F7 areas respectively according to the International 10-20 Electrode Placement System), with 1.5mA current (100–500 Hz). It 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. The impedance of the electrodes was checked before and during the stimulation application to guarantee that it was under 10 kΩ. Electrodes were placed following the International 10-20 System (Trans Cranial Technologies, 2012). The stimulated electric field of each condition electrode placement can be seen in Figure 11.

**Figure 11**

*Electrode placement for the stimulation condition of the study (tRNS).*



*Note*: Electrode montage influence map provided by the Stim Weaver software (Neuroelectrics Inc., Barcelona) based on a realistic head model (Miranda et al., 2013).

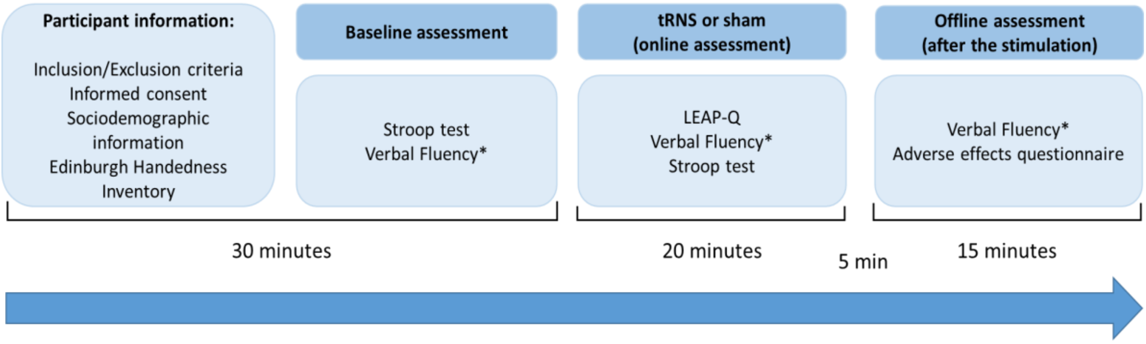
### *4.3.4 Study design and procedure*

The study had 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). Therefore, half of the group received tRNS and the other half the sham condition. In addition, for both conditions, the order of the letters and categories of the verbal fluency tests were counterbalanced across participants. Also, at the beginning of the assessment, participants were also asked if they had slept less or more hours than normal or drunk more or less stimulant beverages than usual.

All participants were tested individually in one single session (see Figure 12). The session was divided into three parts: (1) baseline, (2) online, and (3) offline assessment (see *Figure 2* for procedure details). In the first part, the participants' baseline scores were assessed on the SCWT, the phonemic fluency (two letters for Spanish and for English, one letter for Basque) and semantic fluency (one category per language) tasks. After that, during the second part of the assessment, the participant had to complete the LEAP-Q questionnaire and, while receiving 20 minutes of tRNS, had to perform the semantic and phonetic (two letters for Spanish and English, one letter for Basque) fluency tasks, and the SCWT. In the third part, the neoprene cap was removed, and after a brief rest, the participants had to complete the verbal fluency tasks without any stimulation (offline). Finally, the session was closed with the questionnaire of adverse effects of the stimulation.

**Figure 12**

*General procedure of the study.*



*Note*: Verbal Fluency*= phonemic and semantic tasks were counterbalanced across participants, 5 min = participants had a five-minute break after the stimulation finished.

### *4.3.5 Statistical analysis*

The statistical analyses were carried out using SPSS version 27 for Windows (IBM Corp, 2020). The normality of the data was calculated with Shapiro-Wilk test. Descriptive analyses were performed to show in more detail the baseline characteristics of the participants. Analysis of variance (ANOVA) and Chi-squared tests ($\chi 2$) were also used to analyse between-groups differences by age, years of education, handedness, number of slept hours and consumed stimulants (e.g., coffee, tea, energy drinks, etc.), and their baseline performance in the verbal fluency tasks and the Stroop test. T-test analyses were also carried out to detail the linguistic profile of the participants.

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

We reported partial eta-squared ($\eta_p^2$) effect size in ANCOVA. For the intervals of interpretation of $\eta_p^2$, 0.01 was considered small effect, 0.06 indicated medium effect and 0.14 large effect (Cohen, 1988).

# V. Results

# 5 Results

## 5.1 Study I

### *5.1.1 Characteristics of the included studies.*

In the present meta-analytic review, 16 effect sizes from nine different trials that included 279 healthy participants were estimated. The studies were published between 2008 and 2020 and investigated foreign language learning processes (using non-words, artificial grammar, or foreign vocabulary tasks). From the 16 effect sizes calculated, nine were for language learning accuracy, four for response times and three for the effects of tES one week after the stimulation. The other three studies used HD-tDCS on the left posterior hemisphere with a current intensity of 1mA (Perceval et al., 2017), and tACS on Wernicke's area for 20 minutes and the same current intensity as the previous one (Antonenko et al., 2016). The last one used high frequency (100-600Hz) tRNS with a bilateral set-up (Pasqualotto et al., 2015). A summary of the selected studies is displayed in *Table 3*. None of them reported significant adverse effects from the stimulation. The mean overall effect size (Hedges´g) was 0.51, with a 95% confidence interval (C.I.) between 0.356 and 0.664. The results of the heterogeneity test indicated low levels of heterogeneity and were not significant ($Q$ = 17.44, $p$ = .293; $I^2$ = 14%) (see Tables 4-5*).*

**Table 3**

*Summary of the reviewed studies with sham condition in studying the effects of tES on language learning.*

| Author | Sample | Age (mean) | Years of education | Study design | Sham? | Task | tES | Stimulated Area | Stimulation details (mA; min, …) | Stimulation effects/Results |
|---|---|---|---|---|---|---|---|---|---|---|
| (Flöel et al., 2008) | 19 | 25.6 | 16-22<br>(18.7±0.4) | Double-blind<br>Randomized<br>Crossover<br>Within-subject<br>1 session<br>Online | Yes | Non-word learning | tDCS<br>A, C | A = Wernicke’s area (CP5)<br>C = contralateral supraorbital region. | 1mA<br>5x7 cm sponge<br>20 min | Significantly better language learning with anodal stimulation; however, the effects vanished after one week. |
| (De Vries et al., 2010) | 38 (19 exp, 19 cntrl)<br>+10 post hoc | 22.6 | (15.6±1.5) | Randomized<br>Between-subject<br>1 session<br>Online/offline | Yes | Artificial grammar learning | tDCS<br>A | A = Broca’s area<br>Ref = contralateral supraorbital región (rSO) | 1mA<br>5x7 cm sponge<br>20 min | No group differences in the artificial grammar acquisition task, but there is a trend in favour of tDCS group. |
| (Fiori et al., 2011) | 10 HP<br>3 SP | 55 | 8-17<br>(14±2.4) | Double blind<br>Randomized<br>Counter-balanced<br>Within-subject<br>1 session<br>Online | Yes | Non-word learning | tDCS<br>A | A = Wernicke's área (CP5)<br>A = right occipito-parietal area | 1mA<br>5x7 cm sponge<br>20 min | Beneficial effects of atDCS on Cp5 during word learning, recognition, and name retrieval. |
| (Meinzer et | 40 (20 | 23.9 | tDCS | Randomized | Yes | Non- | tDCS | A = left posterior | 1mA | Anodal tDCS |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| al., 2014) | exp, 20 cntrl) | | (15.7±1.4)<br>Sham<br>(15.9±1.6) | Between-subject<br>5 sessions<br>Online/offline | | word learning | A, C | temporoparietal junction<br>C= contralateral supraorbital region | 5x7 cm sponge<br>20 min | facilitates learning with multiple applications and effects are maintained over time. |
| (Pasqualotto et al., 2015) | 54 (18 exp., 18 exp., 18 cntrl) | 21.48 | N/A | Randomized<br>Between-subject<br>1 session<br>Online/offline | Yes | Foreign words learning (Swahili) | tRNS bilateral high frequency (100-600 Hz) | DLPFC (F3, F4)<br>Posterior parietal cortex (P3, P4) | 1mA<br>5x5 cm sponges<br>25 min | Posterior parietal stimulation may be implicated in foreign language learning. No differences between groups on overall learning after the first session. However, one week later, there was an improvement in those who received the stimulation. |
| (Antonenko et al., 2016) | 24 (12 young adults; 12 older adult) | 22.3 (Young adults)<br>66.3 (Older | Young adults (15.5±1.4)<br>Older adults (15.8±3.2) | Randomized<br>Single-blind<br>Crossover<br>Within-subject<br>Between-subject | Yes | Non-words | tACS bilateral 6Hz | One electrode = Temporoparietal cortex, Wernicke´s area (CP5) | 1mA<br>5x7 cm sponges<br>20 min | Implicit language learning performance improved after |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | adults) | | Online | | | | Ref = right supraorbital area | | receiving tACS, comparing to sham condition. Superior performance of older adults in tACS, comparing to sham condition. |
| (Fiori et al., 2017) | 30 (15 young adults; 15 older adult) | 29 (Young adults) (Older adults) | Young adults (17±6)<br>Older adults (17±2) | Randomized<br>Double-blind<br>Within-subject<br>Counterbalanced | Yes | Non-words | tDCS<br>A, C | Unihemipheric group:<br>A = Left temporal area (CP5)<br>C = rSO<br>Bihemispheric group:<br>A = CP5<br>C = CP4 | 2mA<br>5x7 cm sponges<br>20 min | No significant differences on performance between young groups' different conditions. Better performance of bihemispheric condition in elderly groups |
| (Perceval et al., 2017) | 50 (25 exp., 25 cntrl) | 23.16 | HD-tDCS (13.6±1.7)<br>Sham (13.9±1.4) | Double-blind<br>Randomized<br>Between-subjects<br>1 session<br>Online/offline | Yes | Foreign word learning (Ancient Finnish) and non-words | HD tDCS | A = Left posterior temporal lobe<br>Ref = Fronto-polar cortex | 1mA<br>2.5cm, 7.5 cm, 9.8 cm sponges<br>20 min | No differences between groups on overall learning, however, the stimulated group resulted in overall faster response, a better |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | performance than sham. |
| (Fiori et al., 2018) | 28 | 26.96 | N/A | Within-Subjects Counterbalanced<br>1 session<br>Online/offline | Yes | Foreign verb learning (Italian) | tDCS A, C + fMRI | A = Left inferior frontal gyrus (FC5)<br>C= Contralateral fronto-polar region | 1mA<br>5x7 cm sponges<br>24 min | Behavioural improvements with tDCS condition |
| (Owusu and Burianová, 2020) | 16 | 24.25 | N/A | Randomized<br>Single-blind<br>Within-subjects<br>1 session | Yes | Dominant Subordinate and non-words learning | tDCS A, C | A = Wernicke's area (CP5)<br>C = Right supraorbital ridge (FP2) | 1.5 mA<br>4x4 cm<br>20 min | Better performance on non-words recalls with anodal tDCS, comparing with the sham group. |
| (Perceval et al., 2020) | 101 (41 young adults. 60 older adults) | 21.44 (young adults)<br>67.05 (older adults) | Young adults (14.43±1.2)<br>Older adults (14.12±2.13) | Randomized<br>Double-blind<br>Between-subjects<br>5 sessions<br>Online | Yes | Non-words | tDCS A, C | A = Left inferior frontal gyrus<br>C = Contralateral supraorbital region | 1mA<br>5x7 cm sponges<br>20 min | Multisession tDCS improved verbal associative learning and its maintenance. tDCS improved learning and memory in participants with lower baseline learning scores. In young adults: no immediate effects, tDCS |

| | |
|---|---|
| | helped on information maintenance. |

*Note*. Exp = experimental condition; cntrl = control-placebo condition; A = anodal stimulation; C = cathodal stimulation; Ref = reference electrode; DLPFC = dorsolateral prefrontal cortex.

**Table 4**

*All 16 estimated effect sizes with 95% CI and percentage weight.*

| | **Hedges´ g** | **95% CI** | | **% Weight** |
|---|---|---|---|---|
| | | **CI Lower** | **CI Upper** | |
| **Accuracy** | | | | |
| Flöel et al., 2008 | .622 | - .028 | 1.273 | 4.6 |
| De Vries et al., 2010 | .677 | .044 | 1.310 | 8 |
| Fiori et al., 2011 | .281 | - .540 | 1.102 | 2.7 |
| Meinzer et al., 2014 | .697 | .078 | 1.316 | 8.3 |
| Pasqualotto et al., 2015 | .382 | - .253 | 1.017 | 7.9 |
| Antonenko et al., 2016 | .728 | .143 | 1.312 | 5.5 |
| Perceval et al., 2017 | .153 | - .388 | .694 | 10.2 |
| Fiori et al., 2018 | .727 | .186 | 1.268 | 6.3 |
| Owusu et al., 2020 | .559 | - .119 | 1.237 | 3.9 |
| **Response times** | | | | |
| Flöel et al., 2008 | .120 | - .516 | .756 | 4.8 |
| Fiori et al., 2011 | .908 | -.012 | 1.828 | 2.5 |
| Perceval et al., 2017 | .826 | .417 | 1.234 | 9.6 |
| Owusu et al., 2020 | .091 | -.544 | .727 | 4.8 |
| **Follow up** | | | | |
| Flöel et al., 2008 | .164 | -.472 | .800 | 4.8 |
| Meinzer et al., 2014 | .747 | .293 | 1.20 | 8.3 |
| Pasqualotto et al., 2015 | .522 | .052 | .991 | 7.8 |

| **Summary** | **Hedges' g** | **95% CI** | | ***p*** | **Heterogeneity** | | |
|---|---|---|---|---|---|---|---|
| | | **CI Upper** | **CI Lower** | | **Q** | ***p*** | **$I^2$ (%)** |
| | .510 | .356 | .664 | .000 | 17.44 | .293 | 14% |

**Table 5**

*Summary of effects sizes of each area.*

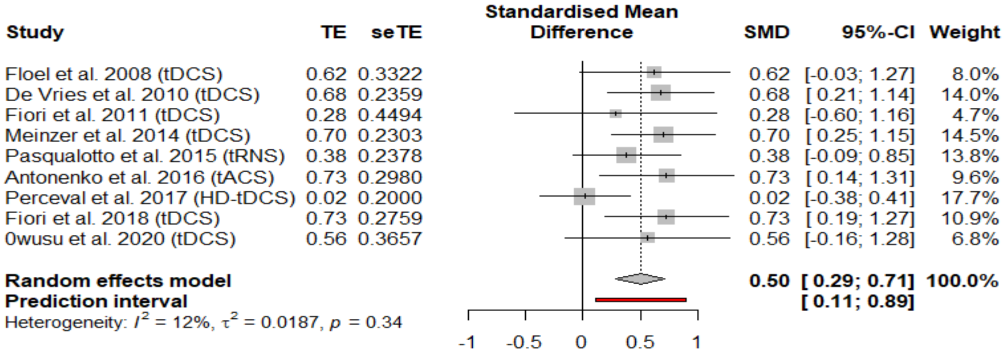
| | **Hedges' g** | **95% CI** | | | **Heterogeneity** | | |
|---|---|---|---|---|---|---|---|
| | | **CI Lower** | **CI Upper** | ***p*** | **Q** | ***p*** | **$I^2$ (%)** |
| Accuracy (Overall learning) | 0.501 | .289 | .713 | .000 | 9.08 | .335 | 11.9% |
| Response times | 0.497 | - .184 | 1.178 | .103 | 2.97 | .108 | 50.6% |
| Follow up (1 week after) | 0.540 | -.120 | 1.200 | .072 | 2.15 | .342 | 6.8% |

### 5.1.2 *Overall effects of tES on language learning success*

Overall learning accuracy results seem to indicate that tES has a positive effect on foreign language learning processes in healthy participants. The overall effect size (Hedges's g) of tES in language learning accuracy was 0.50 (95% C.I. = 0.289 – 0.713; *p* = .0006). These results have shown an overall moderate effect of tES on foreign language learning processes in healthy adults, an effect that is significantly different from zero. The homogeneity tests showed low levels of heterogeneity (Q = 9.08, *p* = .336; $I^2$ = 12%), which could mean that tES may have an important effect on the language learning processes. The results are shown in Figure 13.

**Figure 13**

*Overall learning (accuracy) effect sizes of all the included studies.*



| **Study** | **TE** | **seTE** | **SMD** | **95%-CI** | **Weight** |
|---|---|---|---|---|---|
| Floel et al. 2008 (tDCS) | 0.62 | 0.3322 | 0.62 | [-0.03; 1.27] | 8.0% |
| De Vries et al. 2010 (tDCS) | 0.68 | 0.2359 | 0.68 | [ 0.21; 1.14] | 14.0% |
| Fiori et al. 2011 (tDCS) | 0.28 | 0.4494 | 0.28 | [-0.60; 1.16] | 4.7% |
| Meinzer et al. 2014 (tDCS) | 0.70 | 0.2303 | 0.70 | [ 0.25; 1.15] | 14.5% |
| Pasqualotto et al. 2015 (tRNS) | 0.38 | 0.2378 | 0.38 | [-0.09; 0.85] | 13.8% |
| Antonenko et al. 2016 (tACS) | 0.73 | 0.2980 | 0.73 | [ 0.14; 1.31] | 9.6% |
| Perceval et al. 2017 (HD-tDCS) | 0.02 | 0.2000 | 0.02 | [-0.38; 0.41] | 17.7% |
| Fiori et al. 2018 (tDCS) | 0.73 | 0.2759 | 0.73 | [ 0.19; 1.27] | 10.9% |
| 0wusu et al. 2020 (tDCS) | 0.56 | 0.3657 | 0.56 | [-0.16; 1.28] | 6.8% |
| **Random effects model** | | | **0.50** | **[ 0.29; 0.71]** | **100.0%** |
| **Prediction interval** | | | | **[ 0.11; 0.89]** | |

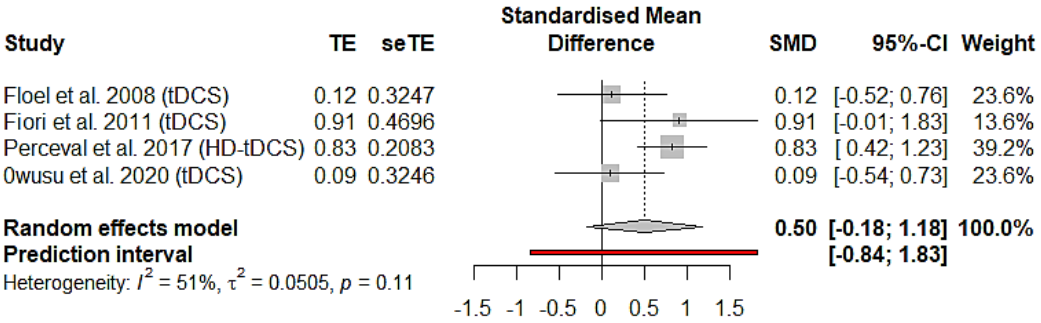
Heterogeneity: $I^2 = 12\%$, $\tau^2 = 0.0187$, $p = 0.34$

### 5.1.3 *Effects of tES on response times.*

The results showed a non-significant medium overall effect size (*g* = 0.50, 95% C.I. = -.184 – 1.18; *p* = .103) and a moderate but non-significant level of heterogeneity (Q = 6.08, *p* = .108; $I^2$ = 50.6%). These results could indicate that tES has no effect on learning or response speed in related language learning tasks. Results are displayed in Figure 14.

**Figure 14**

*Response times of participants during the learning tasks.*

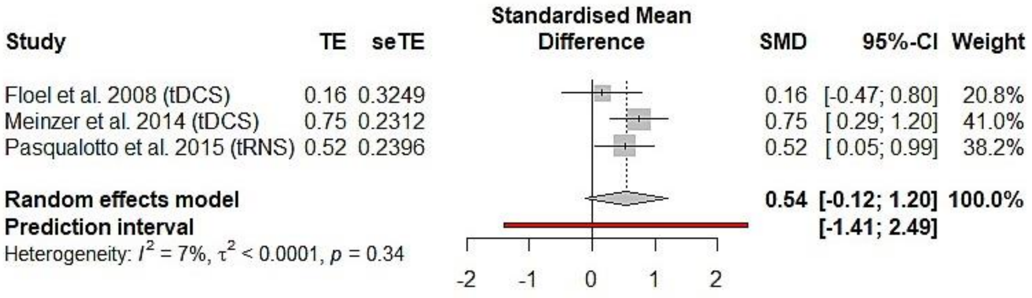


### 5.1.4 *Duration of tES enhancement effects one week after stimulation*

The results showed a non-significant moderate overall effect size (*g* = 0.54, 95% C.I. = -.12 – 1.20; *p* = .07) and a low and non-significant level of heterogeneity (Q = 2.15, *p* = .342; $I^2$ = 6.8%). These results could indicate that the possible benefits of tES were not noticeable seven days following tES. Results are displayed in Figure 15.

**Figure 15**

*Follow up of tES effects one week after receiving the stimulation.*



### *5.1.5 Meta-regression analyses*

Meta-regression analyses were performed to explore whether effect size differences could be related to the characteristics of the participants (mean age and years of education) or the characteristics of the trials, specifically type of trial design (within-subject or between-subject) and number of tES sessions conducted (one or several). Moderator analyses results are summarized in Table 6.

The main analyses (models 1 to 4) showed that only the years of education variable (model 2) was a significant predictor ($F_{(1,\ 6)} = 6.67$, $\beta = .15$, $p = .04$) when applying tES for the conducted of foreign language learning processes. This suggests that tES could have a greater impact on foreign language learning processes for participants with more years of education. The results of the rest of the analyses (models 1, 3 and 4) were not significant ($p > .05$).

**Table 6**

*Results of moderator analyses.*

| ***Model number*** | ***Predictor variables*** | ***K*** | ***df*** | $Q_{residual}$ | $F_{moderator}$ | $R^2$ | $\beta$ | ***p*** |
|---|---|---|---|---|---|---|---|---|
| 1 | Age | 9 | 7 | 8.86 | .12 | 11.51% | .004 | .738 |
| 2 | Years of Education | 8 | 6 | 3.90 | 6.67 | 100% | .150 | **.041*** |
| 3 | Type of design (within vs. between-subject) | 9 | 7 | 7.61 | 1.30 | 52.32% | .215 | .291 |
| 4 | Number of sessions | 9 | 7 | 8.11 | .77 | 37% | -.233 | .410 |

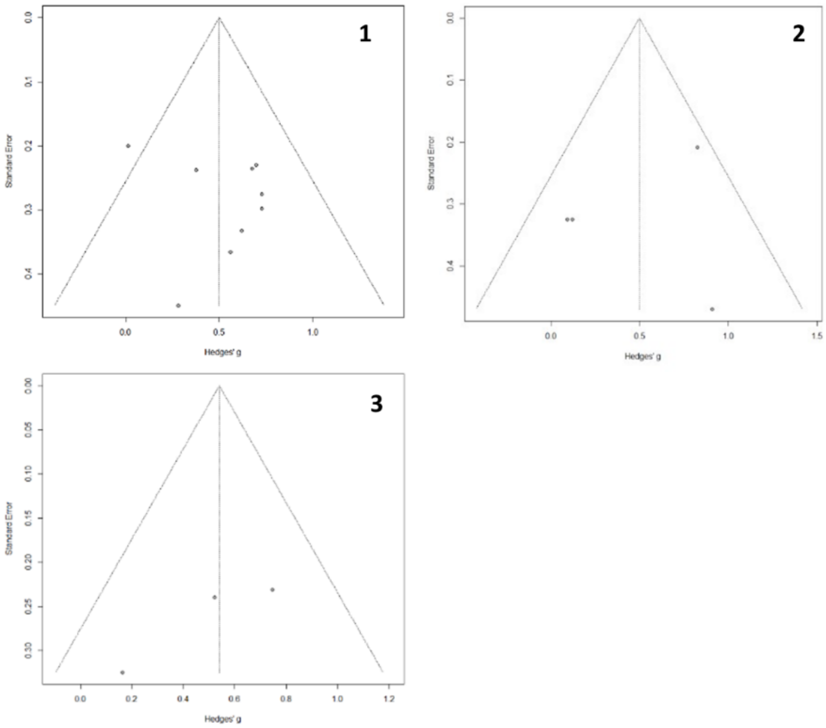
*Note:* K = number of studies; $R^2$ = percentage of explained heterogeneity; $\beta$ = estimate; *$p < .05$.

### *5.1.6 Publication bias*

A funnel plot and Egger’s Regression test (Egger et al., 1997) were conducted to assess potential publication bias. The funnel plots can be seen in Figure 16. The data showed no publication bias in the different areas analysed (accuracy, *p* = .76; response times, *p* = .62; follow-up, *p* = .24). However, it should be noted that the statistical power of Egger´s Regression test may be reduced when the number of studies is small (k <10) (Egger et al., 1997; Sterne et al., 2011).

**Figure 16**

*Funnel plots that show publication bias for: (1) accuracy measure of the studies; (2) response time's measures of the trials and (3) follow up measures.*



### 5.1.7 Sensitivity analysis

The results can be seen in the supplementary material (Figures S6-S7). The sensitivity analyses showed small changes in accuracy effect sizes when removing the study with multiple stimulation sessions (from g = 0.50, *p* = .000 to g = 0.47, *p* = .002), and when using an r of .4 (from g = 0.50, p = .000 to g = 0.50, *p* = .001) or .8 (from g = 0.50, *p* = .000 to g = 0.54, *p* = .000) for between-subject design studies. Changes could also be observed in response times effect size outcomes when using an r of .4 (from g =

0.50, *p* = .103 to *g* = 0.44, *p* = .11) or .8 (from *g* = 0.50, *p* = .103 to *g* = 0.56, *p* = .11) for between-subject design studies.

## 5.2 Study II

### *5.2.1 Sociodemographic characteristics of the groups*

Baseline variables of the groups are shown in Table 7. No significant differences were found among the groups in terms of age, sex, years of education, handedness, in the consumption of stimulant drinks (e.g., tea, coffee, energy drinks) and number of sleep hours before the evaluation.

**Table 7**

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

| | **tDCS (n = 16)** | **tRNS (n = 16)** | **tDCS-tRNS (n = 16)** | **Sham (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 | .385 |
| Years of education | 15.81 (3.06) | 17.06 (3.02) | 16.25 (2.64) | 16.62 (1.96) | $F$= .62 | .601 |
| Sex: n (%) | | | | | $X^2$= .96 | .811 |
| 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 | .410 |
| Number of slept hours | 6.77 (1.18) | 6.95 (0.68) | 7.34 (1.18) | 6.96 (1.26) | $F$= 1.07 | .368 |
| Number of stimulants | 0.81 (1.16) | 0.96 (1.19) | 0.69 (0.87) | 0.81 (0.98) | $F$= .20 | .904 |

*Note*: M = Mean; SD = Standard Deviation.

### 5.2.2 *Overall effects of tES on foreign vocabulary learning*

All the results obtained by the participants are displayed in Table 8. In the learning session, there were no statistically significant differences in learning between the stimulation (tDCS, tRNS and tDCS/tRNS) and sham groups ($F_{(1, 61)} = .86$; $p = .36$; $\eta_p^2 = .01$). Likewise, when comparing each experimental condition separately, no statistically significant differences were found ($F_{(3, 59)} = 1.33$; $p = .27$; $\eta_p^2 = .06$).

In the follow-up session, two weeks later, statistically significant differences were observed between the stimulation group and sham group ($F_{(1, 59)} = 5.55$; $p = .022$; $\eta_p^2 = .08$). Such differences were also observed in the marginal means (corrected by prior baseline knowledge of the foreign language) obtained by the stimulation group ($M = 16.51$; $SE = 1.04$) and the placebo group ($M = 11.73$; $SE = 1.70$). When comparing each experimental condition separately, there were significant differences between the 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. Details of the follow-up *post hoc* results are shown in Table 9.

**Table 8**

*Differences in the number of correct English words (marginal means) remembered and learned by the participants in the first learning session (single stimulation session) and at follow-up (two weeks later).*

| | ***tDCS*** | | ***tRNS*** | | ***tRNS-tDCS*** | | ***Sham*** | | ***ANCOVA*** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***M*** | ***SE*** | ***M*** | ***SE*** | ***M*** | ***SE*** | ***M*** | ***SE*** | ***df*** | ***MS*** | ***F*** | ***p*** | $\eta_p^2$ |
| First session | 18.66 | 1.87 | 19.44 | 1.87 | 15.06 | 1.86 | 15.69 | 1.89 | ***3*** | 73.21 | 1.33 | .271 | .06 |
| Follow-up | 16.70 | 1.67 | 18.59 | 1.74 | 13.95 | 1.73 | 11.74 | 1.70 | 3 | 137.21 | 3.09 | **.034*** | .14 |

*Note: M*= Mean; *SE* = Standard Error; *Stimulation group (merged)* = all the participants who received tES; *all groups= tDCS vs. tRNS vs. tRNS-tDCS vs. sham comparison*.

**Table 9**

*Results of pairwise comparisons of all the groups on the follow-up.*

| **Experimental Condition Comparison** | | **MD (SE)** | ***p*** | **95% C.I.** | |
|---|---|---|---|---|---|
| | | | | **Lower limit** | **Upper limit** |
| Placebo | tDCS | -5.02 (2.38) | .229 | -11.51 | 1.48 |
| | tRNS | -6.91 (2.43) | **.037*** | -13.56 | -.26 |
| | tDCS & tRNS | -2.27 (2.39) | 1.00 | -8.82 | 4.27 |
| tDCS | tRNS | -1.89 (2.38) | 1.00 | -8.44 | 4.66 |
| | tDCS & tRNS | 2.74 (2.41) | 1.00 | -3.84 | 9.33 |
| tRNS | tDCS & tRNS | 4.64 (2.46) | .389 | -2.09 | 11.37 |

*Note*: *MD* = mean difference; *SE* = Standard Error.; * $p < 0.05$.

### *5.2.3 Effects of other variables on learning performance*

We analysed 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 (*β*= -.47 [-2.31 - 1.36], *SE*= .92, *t*= -.52, *p* = .60).

### *5.2.4 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 10). In general, participants reported not being able to distinguish whether they had received active or sham stimulation.

**Table 10**

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

| **Adverse effects** | **tDCS N (%)** | **tRNS N (%)** | **tDCS-tRNS N (%)** | **Placebo N (%)** | $X^2$ | ***p*** |
|---|---|---|---|---|---|---|
| Headache | 2 (12.50) | 4 (25) | 2 (12.50) | 1 (6.25) | 2.37 | .501 |
| Throat sore | 0 (0) | 0 (0) | 1 (6.25) | 0 (0) | 3.05 | .409 |
| Scalp pain | 0 (0) | 2 (12.50) | 0 (0) | 0 (0) | 6.19 | .110 |
| Skin tingling | 5 (31.25) | 8 (50) | 4 (25) | 5 (31.25) | 7.76 | .612 |
| Skin itching | 6 (37.50) | 8 (50) | 3 (18.75) | 4 (25) | 5.39 | .369 |
| Skin burning sensation | 1 (6.25) | 2 (12.50) | 0 (0) | 1 (6.25) | 3.95 | .687 |
| Redness of the skin | 0 (0) | 1 (6.25) | 0 (0) | 0 (0) | 3.05 | .401 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Numbness | 1 (6.25) | 2 (12.50) | 0 (0) | 2 (12.50) | 5.54 | .431 |
| Concentration problems | 1 (6.25) | 2 (12.50) | 3 (18.75) | 2 (12.50) | 2.69 | .675 |
| Mood change | 0 (0) | 1 (6.25) | 0 (0) | 1 (6.25) | 2.02 | .579 |
| Phosphenes | 0 (0) | 1 (6.25) | 0 (0) | 1 (6.25) | 2.02 | .579 |

## 5.3 Study III

### *5.3.1 Sociodemographic characteristics*

Baseline variables of the groups can be seen in Table 11. There were no significant differences between the groups in age, years of education, sex, handedness, in the number of stimulant drinks consumed (e.g., coffee, tea, energy drinks) and number of hours slept prior to the evaluation.

**Table 11**

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

| | **tRNS group (n = 25)** | | **Sham group (n = 25)** | | | |
|---|---|---|---|---|---|---|
| | **Mean (Range)** | **SD** | **Mean (Range)** | **SD** | **Statistic** | ***p*** |
| Age | 24.84 (18 to 47) | 7.93 | 22.24 (18 to 30) | 5.19 | *F* = 1.47 | .169 |
| Years of education | 15.40 (12 to 23) | 3.29 | 15.40 (11 to 24) | 3.34 | *F* = .00 | 1.000 |
| Sex: n (%) | | | | | $\chi^2$ = 2.59 | .110 |
| Female participants | 21 (84%) | | 16 (64%) | | | |
| Male participants | 4 (16%) | | 9 (36%) | | | |
| Edinburgh Handedness | 13.96 (10 to 43) | 6.61 | 13.88 (10 to 28) | 4.23 | *F* = .00 | .961 |
| Number of slept hours | 6.68 (4 to 9) | 1.18 | 7.20 (5 to 9) | 0.91 | *F* = 3.03 | .082 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Number of stimulants | 0.56 (0 to 2) | 0.71 | 0.68 (0 to 2) | 0.69 | *F* = 0.36 | .554 |

*Note*: SD = Standard Deviation.

### *5.3.2 Linguistic profile: LEAP-Q*

The linguistic profile of the participants can be seen in Table 12. No significant 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 the participants were very similar, with no differences in the language areas assessed by the LEAP-Q. However, in the Basque language, statistically significant differences were observed between the groups in the item "listening to radio/music" in the domains of contribution to language learning ($p$ = 0.01) and exposure and use ($p$ = 0.03). These results would indicate a greater contribution to Basque language learning from music listening 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.

**Table 12**

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

| | **tRNS Basque** | | **Sham Basque** | | | **tRNS English** | | **Sham English** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | **M** | **SD** | **M** | **SD** | ***p*** | **M** | **SD** | **M** | **SD** | ***p*** |
| Age of acquisition | 2.55 | 2.26 | 3.33 | 1.56 | .94 | 7.36 | 6.82 | 6.40 | 2.24 | .51 |
| **Self-evaluation** | | | | | | | | | | |
| Speaking (1-10) | 6.10 | 2.79 | 5.71 | 2.25 | .61 | 6.12 | 2.31 | 6.16 | 2.11 | .95 |
| Comprehension (1-10) | 7.65 | 2.10 | 7.71 | 2.03 | .93 | 6.92 | 2.45 | 7.40 | 2.23 | .47 |
| Reading (1-10) | 7.70 | 1.95 | 7.60 | 2.04 | .85 | 7.04 | 2.19 | 7.60 | 1.58 | .31 |
| **Contribution to learning** | | | | | | | | | | |
| Interacting with friends (0-10) | 3.90 | 3.77 | 4.50 | 2.75 | .55 | 2 | 3.01 | 1.40 | 2.65 | .46 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Interacting with family (0-10) | 2.15 | 2.98 | 2.17 | 3.13 | .99 | 1.92 | 2.80 | 1.80 | 3.24 | .89 |
| Reading (0-10) | 5.85 | 2.85 | 5.29 | 2.82 | .52 | 5.12 | 3.51 | 5.08 | 3.45 | .97 |
| Language self-learning (0-10) | 6 | 3.01 | 5 | 3.50 | .32 | 7.08 | 2.93 | 6.68 | 3.53 | .66 |
| Watching TV (0-10) | 4.80 | 3.33 | 5.58 | 2.40 | .37 | 5.68 | 3.32 | 4.32 | 3.37 | .16 |
| Listening to radio/music (0-10) | 2.25 | 2.83 | 4.71 | 3.04 | **.01*** | 4.64 | 3.67 | 4.32 | 3.18 | .74 |
| **Exposure and use** | | | | | | | | | | |
| Interacting with friends (0-10) | 3.30 | 3.69 | 2.54 | 2.72 | .44 | 2.32 | 2.97 | 1.68 | 2.73 | .43 |
| Interacting with family (0-10) | 1.25 | 2.02 | 1.29 | 2.11 | .95 | .88 | 2.03 | .48 | 1.69 | .45 |
| Reading (0-10) | 3.10 | 4.05 | 2.00 | 2.55 | .28 | 5 | 3.16 | 4.72 | 3.95 | .78 |
| Language self-learning (0-10) | 1.65 | 3.05 | 2.54 | 3.36 | .37 | 2.40 | 3.37 | 1.96 | 3.42 | .65 |
| Watching TV (0-10) | 2.05 | 2.80 | 1.79 | 2.37 | .74 | 5.36 | 3.64 | 5.24 | 3.71 | .91 |
| Listening to radio/music (0-10) | 2.40 | 2.91 | 4.33 | 2.75 | **.03*** | 5.40 | 3.73 | 5.80 | 3.27 | .69 |

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

### 5.3.3 *Effects of tRNS on verbal fluency and SCWT test*

All the verbal fluency test results obtained by the participants are displayed in *Table 13-14.* No differences were reported between groups in the baseline performance on the verbal fluency tasks ($F$ ranged from 0.03 to 1.11, and $p$ ranged 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 online assessment ($F = 3.75$, $p = 0.059$). Thus, the analyses indicate a higher number of words generated by participants who received the tRNS condition compared to sham in the native (Spanish) and English language. In Basque, no statistically significant differences were observed in the online and offline assessment of the phonemic fluency test, which may be due to the sample size used for this language, since a better performance was observed in the tRNS (*M* = 12.52, *SE* = 0.73), than in sham (*M* = 10.88, *SE* = 0.70) in 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), neither during the stimulation (online) nor afterwards (offline).

On the other hand, in the Stroop test, statistically significant differences were only observed in the colour-word part (*F* = 7.60, *p* = 0.008) during stimulation (online assessment), showing a better performance of the participants under the tRNS condition compared to the sham condition.

**Table 13**

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

**Table 14**

*ANCOVA of the verbal fluency scores obtained by the 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*** | $\eta_p^2$ |
| Spanish | Phonemic | Online | 35.04 | 1.27 | 30.88 | 1.27 | 5.31 | **.026*** | .10 |
| | | Offline | 32.14 | 1.23 | 27.69 | 1.23 | 6.44 | **.015*** | .12 |
| | Semantic | Online | 23.12 | 1.24 | 21.48 | 1.24 | .86 | .357 | .02 |
| | | Offline | 18.58 | .83 | 16.70 | .83 | 2.53 | .118 | .05 |
| English | Phonemic | Online | 17.39 | .91 | 14.88 | .91 | 3.75 | .059 | .07 |
| | | Offline | 21.87 | 1.20 | 16.28 | 1.20 | 10.80 | **.002*** | .18 |
| | Semantic | Online | 9.96 | .61 | 8.47 | .61 | 2.95 | .092 | .05 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Offline | 12.56 | .93 | 11.41 | .93 | .74 | .393 | .01 |
| Basque† | Phonemic | Online | 10.87 | .84 | 9.62 | .79 | 1.06 | .310 | .03 |
| | | Offline | 12.74 | .79 | 10.68 | .75 | 3.21 | .082 | .08 |
| | Semantic | Online | 10.98 | 1.03 | 10.52 | .96 | .09 | .756 | .00 |
| | | Offline | 9.48 | 1.00 | 8.66 | .94 | .32 | .575 | .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, * $p < 0.05$.

### *5.3.4 Mediation analysis*

Finally, we examined whether SCWT scores could influence participants' performance on Spanish and English phonemic fluency after having received tRNS. The results shown a non-significant indirect effect of the stimulation on both languages phonemic verbal fluency performance through SCWT (Spanish: $b$ = -0.372, $t$ = -1.788, English: $b$ = 0.092, $t$ = -1.91).

### *5.3.5 Adverse effects*

The participants did not report any serious discomfort or unusual sensations in the scalp. Likewise, no statistically significant differences were observed between the conditions in the reported adverse effects (all $X^2 \leq 2.08$, $p$*'s* $\geq 0.081$). For more details see Table 15.

**Table 15**

*Side effects experienced and reported by participants from tRNS and sham groups.*

| **Adverse effects** | **tRNS N (%)** | **Sham N (%)** | $X^2$ | ***P*** |
|---|---|---|---|---|
| Headache | 2 (8) | 3 (12) | .22 | .637 |
| Sore throat | 0 (0) | 0 (0) | | |
| Scalp pain | 0 (0) | 0 (0) | | |
| Tingling | 0 (0) | 1 (4) | 1.02 | .312 |
| Itching | 0 (0) | 0 (0) | | |
| Burning | 1 (4) | 0 (0) | 1.02 | .312 |

| | | | | |
|---|---|---|---|---|
| Skin redness | 1 (4) | 0 (0) | 1.02 | .312 |
| Numbness | 2 (8) | 0 (0) | 2.08 | .353 |
| Concentration problems | 2 (8) | 3 (12) | 5.02 | .081 |
| Mood change | 0 (0) | 1 (4) | 1.02 | .312 |
| Phosphenes | 0 (0) | 0 (0) | | |

*Note*: tRNS n = 25; Sham n = 25.

# VI. Discussion

# 6 Discussion

The aim of this thesis was to gain further knowledge on the effects of tES on second and foreign language learning processes. For this purpose, three studies were conducted. First, a systematic review and meta-analysis of the literature on the effects of non-invasive brain stimulation techniques on second or foreign-language learning processes in the healthy brain was conducted (*study I*). In addition, the effects of different non-invasive brain electrical stimulation techniques were analysed and their efficacy in the acquisition of new foreign language vocabulary was compared (*study II*). Finally, this thesis explored the effects of one of the least used tES, tRNS, on the performance of verbal fluency tasks in three different languages in healthy multilingual individuals, by stimulating two relevant language brain areas simultaneously (unilateral set-up) (*study III*).

## 6.1 Effects of tES on second/foreign-language learning processes

To date, there is very little research that explores the effects of these techniques on foreign language learning processes, which leaves open many questions about the effects of tES on these processes. Therefore, to provide relevant information and empirical data on the state of the art in tES and foreign language learning processes, we first conducted a systematic review and meta-analysis (*study I*), and then further analysed and compared the effects of different tES on the learning of new foreign language words (*study II*).

The main objective of *study I* was to review and quantify the effects of tES on the processes involved in second or foreign language learning in healthy adults. For this purpose, we examined studies that applied tES techniques (tDCS, HD-tDCS, tACS or tRNS) and used non-words, artificial grammar, and foreign language vocabulary learning tasks. A significant moderate effect of tES on the overall learning process (accuracy) was observed. However, the benefits of tES were non-significant on response times. Overall, the results showed that applying anodal tDCS, HD-tDCS, tACS, or tRNS for 20 to 25 minutes to the language-related brain regions (Wernicke's area, Broca’s area, left frontotemporal area) had moderately significant effects on foreign language learning processes, but had no significant benefits on response times.

The obtained significant positive results were in line and comparable with previous systematic reviews that analysed effects of tES on language (Price et al., 2015; Simonsmeier et al., 2018). A previous meta-analysis reported the effects of a single session of anodal tDCS on language in healthy adults and found a significant effect on language processing compared to sham (Price et al., 2015). Simonsmeier and colleagues (2018), found a strong tES effect on the learning phase of language measures ($d$ = 0.712), showing that tES seems to have stronger effect if administrated during a test performance phase (Simonsmeier et al., 2018).

Notwithstanding the moderate effects reported in our meta-analysis, it is important to bear in mind that there is also evidence of low or no effects of tES on language in healthy population. In 2015, Horvath and colleagues conducted two different systematic reviews where they reported no effects of tDCS in healthy population (Horvath et al., 2015a, 2015b). One study (Horvath et al., 2015b) examined the effects of a single tDCS session on various cognitive measures in healthy adults (executive function, language, memory, and others), and found no significant tDCS effect on any of the cognitive domains chosen. However, this difference with the results obtained in our meta-analysis, could be due to the stimulation objective, the learning paradigms, and the placement of the electrodes of the reviewed studies. In other words, in this thesis we only analysed studies that sought to enhance the learning processes involved in the acquisition of a second or a foreign language, which also stimulated the brain areas that have been found to have a strong association with language acquisition processes (Barbeau et al., 2017; Cohen et al., 2000; Kepinska et al., 2017; Vingerhoets et al., 2003).

The *study II*, on the other hand, aimed to test and compare 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. However, no immediate differences were observed in the learning performance of the participants immediately after the stimulation (first experimental session). Finally, there was no indication that years of education moderated the effects of stimulation on learning performance.

## 6.2 Effects of tES over time: possible long-term effects

Few studies have reported the effects of tES on newly learned information retention; and those that have shown such effects usually performed a one-week follow-up. In the *study I*, only three of the selected studies reported follow-up data one week after tES. Nonetheless, a positive trend toward enhanced newly learned information retention was observed up to one week after the stimulation session. These results could be due to the use of multiple stimulation sessions, which have been shown to have greater beneficial effect (Dockery et al., 2009; Kadosh et al., 2010; Meinzer et al., 2014; Perceval et al., 2020; Reis et al., 2009). It may also be because of tES effect on the brain. According to the literature, tES may facilitate neuronal reactivation during sleep or help consolidate the new information over time (Pasqualotto et al., 2015; Paulus, 2011; Reis et al., 2015; Snowball et al., 2013).

On the other hand, in *study II*, one of the main objectives was to compare the long-term beneficial effects of the different tES (tDCS, tRNS and tRNS/tDCS) on new foreign vocabulary learning. To meet this, a follow-up assessment was carried out two weeks later. Positive effects of the stimulation two weeks later were found; however, no significant differences were observed between the active and sham stimulation groups in the first experimental session (no stimulation effects after a single session).

The results concerning the immediate effects of tES on performance in this study, contrast with data 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 minutes with an intensity of 1mA or 1.5mA (Fiori et al., 2018, 2011; Flöel et al., 2008; Owusu and Burianová, 2020). Some of these studies reported positive tDCS effects using nonword learning tasks (Fiori et al., 2011; Flöel et al., 2008; Owusu and Burianová, 2020), or verbs in a foreign language (Fiori et al., 2018). Nevertheless, while scientific evidence was found of the immediate beneficial effects of stimulation (especially tDCS) (Antonenko et al., 2016; Fiori et al., 2018, 2011; Owusu and Burianová, 2020; Simonsmeier et al., 2018), other similar studies can also be found that observed no beneficial effects of stimulation in a single experimental session (De Vries et al., 2010; Fiori et al., 2017; Pasqualotto et al., 2015; Perceval et al., 2017; Westwood et al., 2017; Westwood and Romani, 2018, 2017), 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 Wernicke’s (Fiori et al., 2017; Perceval et al., 2017) or Broca's area (De Vries et al., 2010) with an intensity of 1mA (De Vries et al., 2010; Perceval et al., 2017), or 2mA (Fiori et al., 2017) for 20 min. They employed nonword learning tasks (Fiori et al., 2017), artificial grammar (De Vries et al., 2010), and foreign vocabulary (Pasqualotto et al., 2015; Perceval et al., 2017).

Referring to the positive effects reported 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 (100-500Hz) tRNS in healthy adults (monolingual, with no previous exposure to the target language) over the DLPFC and posterior parietal cortex (separately) for 20 minutes 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 (Pasqualotto et al., 2015). Also, in a relatively recent published study in which they applied bilateral tDCS for 20 minutes with an intensity of 1-1.5mA over the DLPFC in healthy adults for foreign language learning while using mental imagery (Bolling et al., 2021), 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). In addition to language, other authors have compared tRNS and tDCS in healthy samples in areas such as working memory or motor excitability, among others, observing different results. For example, Murphy and colleagues in 2016 carried out a comparative study of the improvement effects of tRNS and tDCS on working memory in healthy individuals, also providing electrophysiological evidence. The authors observed a more noticeable and consistent improvement in working memory in participants who received tRNS compared to tDCS and sham stimulation (Murphy 2016). Other authors such as Haeckert and colleagues (2020) also observed a greater effect of tRNS compared to tDCS in healthy participants on motor excitability, while others such as Ho and colleagues (2015) observed no difference between the two techniques on motor excitability.

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 (Antal and Herrmann, 2016b; De Ridder et al., 2017; Terney et al., 2008). 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 (De Ridder et al., 2017; Reed and Kadosh, 2018; Snowball et al., 2013). 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 (Bolling et al., 2021; Pasqualotto et al., 2015; Paulus, 2011; Reis et al., 2009; Snowball et al., 2013). Another possibility may be the applied foreign vocabulary-learning task in this study. As in other similar studies, the paradigm used is based on learning by association (in this case, word-picture association), a widely used and effective language learning technique (Meara, 2009). 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 (Snowball et al., 2013).

## 6.3 tES effects on verbal fluency tasks in multilingual healthy adults

To further investigate the effects of tES in language processes when a second or foreign language is involved, the *study III* was conducted. The aim 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 analysed 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 consider when interpreting the results, that fewer participants were tested in Basque (n = 18) than in Spanish (n = 25) and English (n = 25).

Despite the lack of similar studies using tRNS to improve verbal fluency in healthy individuals, the results obtained in this study could be compared with those using tDCS. In fact, the results obtained herein are consistent with previous research where variability in results (both significant and null) has been reported (Westwood et al., 2017; Westwood and Romani, 2018, 2017). In this study, both enhancing and null stimulation effects have been observed. As for the positive effects of stimulation, these were observed in phonemic fluency in the participants' native language in the online and offline assessments, in phonemic fluency in English in the offline assessment, and marginally in the online assessment. Thus, the data suggest that tRNS application focused on a left-brain 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 with previous studies where other authors observed a significant improvement in participants' phonemic fluency (in their native language) after 20 minutes of anodal tDCS when stimulation was applied to the frontotemporal region (Binney et al., 2018), L-DLPFC (Cattaneo et al., 2011), or L-IFG (Pisoni 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-brain 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). However, tRNS only favored phonemic fluency in English in the offline assessment and marginally in the online assessment, with no stimulation effect being observed in Basque. Nevertheless, the results obtained in Basque should be interpreted with caution, as the non-significant effect may be due to the small sample size or other factors related to language characteristics (see Discussion section, p.135). All participants obtained similar results in semantic fluency, regardless of whether they had received tRNS or placebo.

## 6.4 The importance of proper set-up: the need for the establishment of common or standardized protocols in tES and (foreign) language learning processes studies

We hypothesized that in both *studies II* and *III*, regarding the characteristics of the protocol, an important factor influencing the reported findings could be the electrode setup used. Our results are based on a unihemispheric setup, specifically on the proposal previously made by Klaus and Schutter (2018b). As mentioned in the introduction, these authors proposed an alternative electrode setup (both electrodes in the left hemisphere), which could improve the focus on the brain area of interest for tDCS and provide more unequivocal results (Klaus and Schutter, 2018b). This hypothesis is supported by different studies that have investigated the electric fields emitted by tDCS and observed that depending on where and with what intensity the electrode is placed, it can affect the brain area under study to a lesser or greater extent (Laakso et al., 2016; Rampersad et al., 2014). 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 (Rampersad et al., 2014). However, 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, we do not have enough literature to make adequate comparisons.

Another relevant characteristic is the target area of stimulation, which will normally depend on the hypotheses, the task, and the number of tES session. In the studies conducted in this thesis, this methodological decision may have significantly influenced the obtained outcomes. Specifically, in the case of *study III* it could have contributed to the lack of significant improvement of the participants in the semantic verbal fluency tasks, 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 behavioural 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).

Hence, the importance of establishing common, evidence-based stimulation protocols that consider characteristics such as electrode size and placement, duration, and intensity of stimulation, tES time, design -online vs. offline-, type of comparison -between vs. within-, or number of tES sessions, among many other characteristics, among others, is fundamental.

## 6.5 Influence of other variables on the effects of tES on second/foreign-language learning processes and verbal fluency

In addition to the different characteristics to address when establishing an appropriate stimulation protocol (according to our objectives), numerous variables not directly associated with stimulation are relevant to consider because of their potential influence on the results.

In *study I*, given the differences observed between the results of the studies in the meta-analytic review, moderator analyses were carried out to test if there were variables that could affect the studies´ results. In line with previously conducted meta-analyses (Simonsmeier et al., 2018; Westwood and Romani, 2017), positive results of meta-regression analyses were observed. In particular it was found that the participants' years of education could influence the enhancing effect of tES for second or foreign language acquisition, as those participants with more years of education had stronger enhancing effects. These results are consistent with the observations made by Berryhill & Jones (2012) in a study where they applied tDCS in healthy older adults for working memory improvement. They observed that those participants with more years of education performed better than those with fewer years of education when receiving the stimulation (Berryhill and Jones, 2012). This may be due to the beneficial effects of education in the formation of cognitive reserve (Baldivia et al., 2008; Sidenkova et al., 2020; Thow et al., 2018). Many studies discuss the benefits of education in early stages of dementia or other neurodegenerative diseases, reducing its impact (Cobb et al., 1995; Liao et al., 2005; Matyas et al., 2019; Meng and D'Arcy, 2012; Roe et al., 2008).

Furthermore, neuroimaging studies have shown that a greater number of years of education contribute to the reinforcement of neural networks (Fernández-Cabello et al., 2016; Kim et al., 2015). At the same time, a higher level of education may facilitate the use of alternative brain circuits (Liao et al., 2005). Therefore, we may have observed a positive moderating effect of education because higher education may increase the potential benefits of tES, and particularly help individuals with higher levels of education by having reinforced neural networks. Nevertheless, the significance of the results needs to be interpreted with caution, due to the small number of studies available on the subject and the potential statistical consequences of this. Thus, in *study II*, it was investigated whether years of education could influence the effects of stimulation and task performance, as it is also considered a relevant variable in learning processes (Fernández-Cabello et al., 2016; Kim et al., 2015; Liao et al., 2005). However, it was not found to influence the learning performance of the participants. These results are not consistent with previous similar studies, as it has been described. Berryhill & Jones (2012) 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. Nevertheless, the participants of *study II* and *III* were mostly young adults with very similar high education levels, resulting in a very homogeneous sample concerning educational level. This low sample variability could limit the ability to observe the possible real influence of educational level on our results.

Other possible influential variables are related to the different characteristics of the sample. It should be highlighted that, in this thesis, the participants from *study II* and *III* came from a multilingual environment: the Basque Country. 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 favour or interfere with the immediate benefits of stimulation when it comes to improving foreign language learning (Bartolotti and Marian, 2012; Kaushanskaya and Marian, 2009; Kroll and Stewart, 1994; Maluch et al., 2016; Peristeri et al., 2018; Xia et al., 2021). In the case of *study II*, perhaps the multilingual background may have favoured the positive effects of tES in the learning of a foreign language, while in *study III,* being about language production tasks, it may have influenced differently depending on the verbal fluency task (especially in semantic verbal fluency, were no significant tES effects were observed, compared to phonemic verbal fluency). Specifically, in *study III* we assessed the multilingual profile of the participants. 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 behavioural 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 analysing 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).

Finally, in line with linguistic characteristics as an influencing variable, another factor that may have affected the results is language characteristics. In the *study III,* the language on which no apparently significant effect of tES 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. One of the outstanding grammatical features of Basque is its ergative structure, that is, the subject of the transitive verb is placed in the active case; whereas English and Spanish have accusative (or nominative) structures (Laka, 2002; Rezac et al., 2014; Sarkisian, 2001). Additionally, 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; 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, a previous study 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.

On the other hand, another variable that could have affected our results is the participant’s performance in executive function. In *study III*, it was a variable that was considered and assessed with the SCWT. The analysis shown a significant improvement in response time for the colour-word segment 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 analysed (considering set-up type, stimulation intensity, task type, etc.), and positive tDCS effects were observed over the SCWT, especially when the main electrode was applied to the L-DLPFC area (Schroeder et al., 2020). However, no effects on Stroop performance were observed in our study's mediation analyses, thus showing no relationship of SCWT performance on positive tRNS effects on verbal fluency. This may be mainly due to the bilingual profile of the sample. 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).

Finally, 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 (Thair et al., 2017). These factors may also have affected the results obtained in the present thesis studies. For example, the lack of "immediate" improvement of tES in learning new words (*study II*) 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, etc.). In addition, it is important to keep in mind when interpreting the results that 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) (Horvath et al., 2015b).

## 6.6 Limitations and future lines

The three conducted studies present limitations. In *study I* a small number of studies met the inclusion criteria. As mentioned above, there has been little research on the effects of tES on foreign or second language learning processes, and the inclusion criteria we established may have reduced the available sample further. A more extensive analysis and additional results could be obtained if a larger sample of trials were available. Also, the small sample sizes often used in the trials may not reflect a real or true size effect, which could also call into question the several positive results observed by the scientific literature on the effects that tES may have on language (Button et al., 2013; Minarik et al., 2016). Additionally, we were unable to divide and analyse the effects of tES on language depending on the type of stimulation technique used by the studies separately, because of the small sample size available. Furthermore, although we examined years of education as a possible moderating variable, which was positively associated with the effect sizes obtained, these results could have been affected by the small number of studies examined.

Therefore, years of education could be an interesting variable to consider in future research on the effects that tES could have on foreign or second language learning, because a favorable effect of this variable has been observed when applying tES for working memory enhancement in healthy individuals (Berryhill and Jones, 2012). Another variable to take into consideration is the participants’ language learning style. As far as the authors are aware, this variable has not been addressed yet, and could influence the learning process when applying tES. Additionally, participants’ knowledge of another language should be considered, since it has been demonstrated that having learned other languages has an impact on the brain (Laka, 2012). Finally, most of the trials in the present review conducted one tES session, except for the study of Meinzer and colleagues (2014), where five sessions of tES and language learning were held for five consecutive days, which showed better performance of the experimental group and demonstrated increased tES effects on learning (Meinzer et al., 2014). Therefore, we suggest that future studies should hold several stimulation sessions and use various foreign language learning tasks, which could result in language learning processes being more significantly and noticeably enhanced.

In *study II*, 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. In addition, 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 analyse 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.

Regarding *study III*, 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.

Despite these limitations, this thesis provides, on the one hand, novel, and relevant information on the effects of tES on language learning processes applied to healthy population, showing that these techniques may enhance the mechanisms involved in foreign language learning and facilitate language skills such as verbal fluency in multilingual individuals. On the other hand, this thesis has highlighted the importance of the use of other types of tES, such as tRNS, and the need to investigate and develop other types of electrode assemblies for NIBS and language studies. Overall, this thesis aims to expand and improve the knowledge about the effects of tES on language learning processes, their potential and possible scope.

# VII. Conclusions

# 7 Conclusions

## 7.1 Conclusions

The main conclusions of this thesis can be summarized as follows:

- Transcranial electrical stimulation techniques (tES) could have positive effects on the overall second or foreign language learning process in healthy population when applied on the language-related brain areas (Wernicke’s area, Broca’s area, left frontotemporal region) with a 1-2mA current for 20-25 minutes.
- There is a need for further research and replication of studies on the effects of tES on foreign language learning processes to clarify and generate more appropriate protocols for this purpose in healthy populations.
- Unihemispheric montage showed to have beneficial effects on the processes of learning new foreign words and improving performance in phonemic verbal fluency tasks.
- Transcranial random noise stimulation (tRNS) could have a stronger beneficial effect on foreign language learning processes in the long-term. In this thesis, the participants who received tRNS (online acquisition) performed significantly better in recall of the new foreign vocabulary two weeks after learning, in contrast to participants who received the tDCS, tDCS/tRNS or sham condition, in which no significant beneficial effect was observed. On the other hand, no significant enhancement effects of either stimulation technique were observed immediately after stimulation.
- tRNS had beneficial effects on the phonemic fluency task in multilingual individuals (online and offline assessments). Specifically, enhancing effects were observed in Spanish (the native language of the participants) and in English, but not in Basque, which could be because of the small sample of

participants who were tested in Basque compared to Spanish and English, or other reasons (e.g., grammatical characteristics of the Basque language). However, no tRNS enhancing effects were observed on the semantic tasks in any of their known languages (Spanish, English and Basque).

- Years of education was a significant predictor variable when applying tES for learning other languages, suggesting that the effects of stimulation could have a greater impact on foreign language learning processes in individuals with more years of education. Therefore, it is very important to consider other variables when applying tES for foreign language learning.

## 7.2 Conclusiones

Las principales conclusiones de esta tesis pueden sintetizarse de la siguiente manera:

- Las técnicas de estimulación eléctrica transcraneal (tES) podrían tener efectos positivos en el proceso general de aprendizaje de segundas lenguas o lenguas extranjeras en población sana cuando se aplican en las áreas cerebrales relacionadas con el lenguaje (área de Wernicke, área de Broca, región frontotemporal izquierda) con una corriente de 1-2mA durante 20-25 minutos.
- Es necesario seguir investigando y replicando los estudios sobre los efectos de las tES en los procesos de aprendizaje de lenguas extranjeras para esclarecer y generar protocolos más adecuados para este fin en poblaciones sanas.
- El montaje unihemisférico demostró tener efectos beneficiosos en los procesos de aprendizaje de nuevas palabras extranjeras y en la mejora del rendimiento en tareas de fluidez verbal fonémica.
- La estimulación transcraneal de ruido aleatorio (tRNS) podría tener un mayor efecto beneficioso en los procesos de aprendizaje de lenguas extranjeras a largo plazo. En esta tesis, los participantes que recibieron tRNS (adquisición *online*) obtuvieron resultados significativamente mejores en el recuerdo del nuevo vocabulario extranjero dos semanas después del aprendizaje, en contraste con los participantes que recibieron la condición tDCS, tDCS/tRNS o simulada, en los que no se observó ningún efecto significativamente beneficioso. Por otro lado, no se observaron efectos de mejora significativos de ninguna de las dos técnicas de estimulación inmediatamente después de la estimulación.
- tRNS tuvo efectos beneficiosos en la tarea de fluidez fonémica en individuos multilingües (evaluaciones *online* y *offline*). En concreto, se observaron efectos de mejora en español (la lengua materna de los participantes) y en inglés, pero

no en euskera, lo que podría deberse a la pequeña muestra de participantes que se examinaron en euskera en comparación con el español y el inglés u otras razones (por ejemplo, las características gramaticales del euskera). Sin embargo, no se observaron efectos potenciadores del tRNS en las tareas semánticas en ninguna de las lenguas conocidas (español, inglés y euskera).

- Los años de educación fueron una variable predictiva significativa a la hora de aplicar las tES para el aprendizaje de otras lenguas, lo que sugiere que los efectos de la estimulación podrían tener un mayor impacto en los procesos de aprendizaje de lenguas extranjeras en individuos con más años de educación. Por lo tanto, es muy importante tener en cuenta otras variables a la hora de aplicar las tES para el aprendizaje de lenguas extranjeras.

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# IX. Supplementary material

# 9 Supplementary material

**Table S1**

*Search strategy key words used combinations in the CENTRAL and PubMed databases.*

| CONCEPT 1 | | CONCEPT 2 | | | Number of obtained results (n =168) |
|---|---|---|---|---|---|
| (tDCS OR tRNS OR tACS OR transcranial direct current stimulation OR transcranial random noise stimulation OR transcranial alternating current stimulation) | **AND** | (Language learning*) | | | 112 |
| (tDCS OR tRNS OR tACS OR transcranial direct current stimulation OR transcranial random noise stimulation OR transcranial alternating current stimulation) | **AND** | (Foreign language learning* or Second language learning*) | | | 27 |
| (tDCS OR tRNS OR tACS OR transcranial direct current stimulation OR transcranial random noise stimulation OR transcranial alternating current stimulation) | **AND** | (New vocabulary learning* or Novel vocabulary learning*) | | | 11 |
| **CONCEPT 1** | | **CONCEPT 2** | | **CONCEPT 3** | N |
| (tDCS OR tRNS OR tACS OR transcranial direct current stimulation OR transcranial random noise stimulation OR transcranial alternating current stimulation) | **AND** | (Language learning*) | **AND** | (“Healthy adults” or “Healthy participants*”) | 12 |
| (tDCS OR tRNS OR tACS OR transcranial direct current stimulation OR transcranial random noise stimulation OR transcranial alternating current stimulation) | **AND** | (Foreign language learning* or Second language learning*) | **AND** | (“Healthy adults” or “Healthy participants*”) | 5 |
| (tDCS OR tRNS OR tACS OR transcranial direct current stimulation OR transcranial random noise stimulation OR transcranial alternating current stimulation) | **AND** | (New vocabulary learning* or Novel vocabulary learning*) | **AND** | (“Healthy adults” or “Healthy participants*”) | 1 |

**Table S2**

*Methodological quality and risk of bias assessment of the studies (Cochrane Risk of Bias Tool 2.0 for randomized trials and crossover trials)* (Sterne et al., 2019)

| | **Domain** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Article** | **Randomization process** | **Blinding of outcome assessment** | **Missing outcome data** | **Measurement of the outcome** | **Reported results** | **Period and carryover effects*** | **Overall Risk of Bias** |
| **Flöel et al. 2008** | Low | Low | Low | Low | Low | Low | Low |
| **De Vries et al. 2010** | Low | Low | Low | Unclear | Low | | Unclear |
| **Fiori et al. 2011** | Low | Low | Low | Low | Low | Low | Low |
| **Meinzer et al. 2014** | Unclear | Low | Low | Unclear | Low | | High |
| **Pasqualotto et al. 2015** | Unclear | Unclear | Low | Unclear | Low | | High |
| **Antoneko et al. 2016** | Unclear | Unclear | Low | Unclear | Low | Low | High |
| **Fiori et al. 2017** | Low | Low | Low | Low | Low | | Low |
| **Perceval et al. 2017** | Low | Low | Low | Low | Low | | Low |
| **Fiori et al. 2018** | Unclear | Unclear | Low | Unclear | Low | Low | High |
| **Owusu et al. 2020** | Unclear | Unclear | Low | Unclear | Low | | High |
| **Perceval et al. 2020** | Low | Low | Low | Low | Low | | Low |

*Note*: *Period and carryover effects = domain of the risk of bias tool only for crossover trials.

**Table S3**

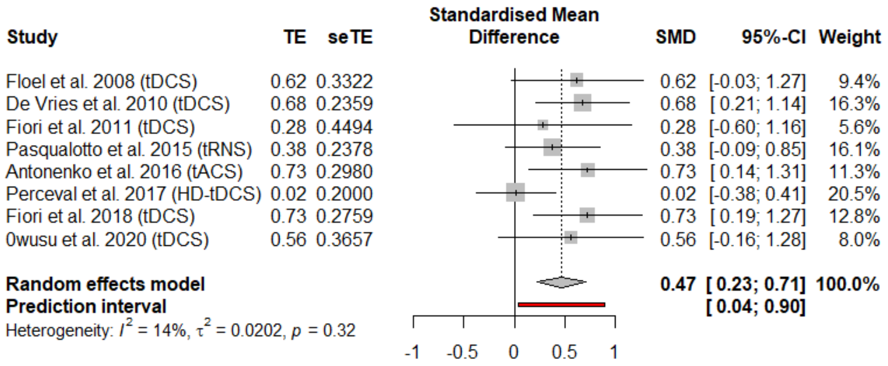
*List of words used in the vocabulary learning paradigm, with the Spanish words and their English counterparts (Moreno-Martínez & Montoro, 2012), and the 55 words added as distractors in the recognition phase.*

| Subcategory | Words (Spanish-English) |
|---|---|
| Animals | Guepardo - Cheetah<br>Ornitorrico - Platypus<br>Suricato - Meerkat |
| Birds | Urraca - Magpie<br>Jilguero - Goldfinch<br>Lechuza - Barn Owl<br>Oca - Goose<br>Gorrión - Sparrow |
| Body parts | Cráneo - Skull |
| Fruits | Grosella - Redcurrant<br>Chirimoya - Custard Apple<br>Cerezas - Cherries |
| Insects | Polilla - Moth<br>Cucaracha - Cockroach<br>Libélula - Dragonfly |
| Dry fruits | Piñón - Pine Kernel<br>Avellana - Hazelnut |
| Vegetables | Repollo-Cabbage<br>Nabo-Turnip<br>Puerro-Leek<br>Apio-Celery |
| Trees | Abeto-Fir<br>Encina - Holm Oak<br>Olivo - Olive Tree<br>Sauce - Willow |
| Buildings | Fábrica - Factory<br>Rascacielos - Skyscraper |
| Food | Morcilla - Black Pudding<br>Filete - Steak |
| Furniture | Librería - Bookcase<br>Atril - Lectern |
| Jewelry | Broche - Brooch<br>Pisacorbatas -Tie Clip |
| Kitchen tools | Cacerola - Saucepan<br>Pelador - Peeler<br>Afilador - Sharpening Steel |
| Musical isntruments | Corneta - Bugle |
| Tools | Tenazas - Pliers<br>Serrucho - Handsaw<br>Llana - Trowel |
| Vehicles | Parapente - Paragliding |
| Weapons | Ballesta - Crossbow |

| | |
|---|---|
| | Bayoneta - Bayonet |
| Nature | Acantilado - Cliff<br>Catarata - Waterfall<br>Carbón - Coal<br>Charco - Puddle<br>Cima - Hilltop |
| Games | Ajedrez - Chess |
| Flowers | Girasol - Sunflower<br>Campanilla - Bellflower<br>Pensamiento - Pansy |
| Office material | Sello - Rubber Stamp<br>Borrador - Eraser<br>Folleto - Leaflet |

## Figure S1.

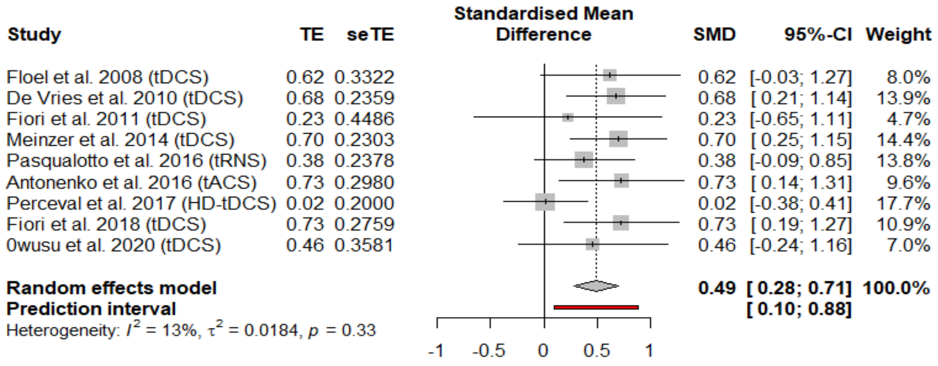
*Sensitivity analyses for accuracy effect sizes without studies with multiple stimulation sessions.*



*Note:* Abbreviations: tDCS, transcranial direct current stimulation; TRNS, transcranial random noise stimulation; tACS, transcranial alternating current stimulation; HD-tDCS, High-Definition transcranial direct current stimulation; TE, Estimate of treatment effect (Hedge´s g; effect size); seTE, Standard error of treatment estimate; SMD, Standardised Mean Difference; CI, confidence interval.

## Figure S2

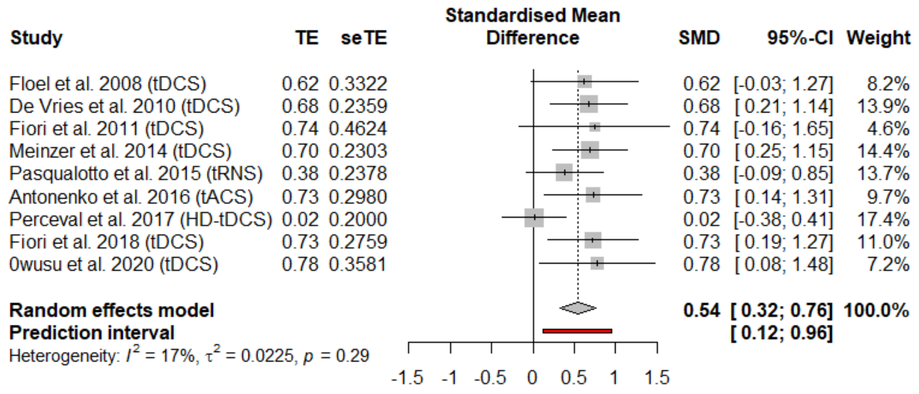
*Sensitivity analyses for accuracy effect sizes with an r = .4 for the within-subject design studies*



*Note:* Abbreviations: tDCS, transcranial direct current stimulation; TRNS, transcranial random noise stimulation; tACS, transcranial alternating current stimulation; HD-tDCS, High-Definition transcranial direct current stimulation; TE, Estimate of treatment effect (Hedge´s g; effect size); seTE, Standard error of treatment estimate; SMD, Standardised Mean Difference; CI, confidence interval.

## Figure S3

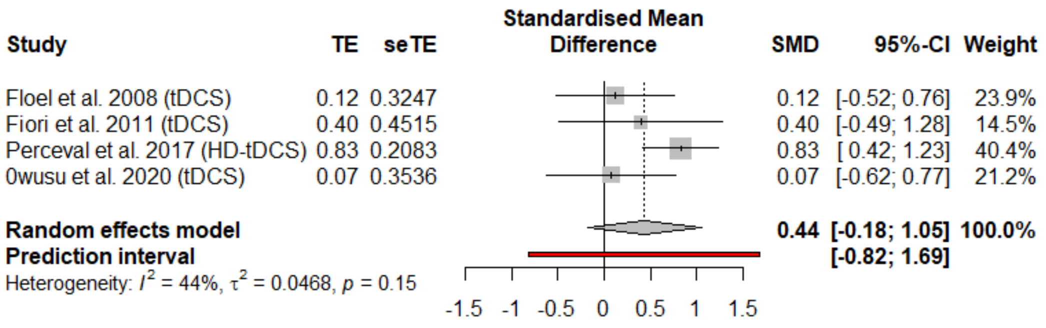
*Sensitivity analyses for response times effect sizes with an r = .8 for the within-subject design studies.*



*Note:* Abbreviations: tDCS, transcranial direct current stimulation; TRNS, transcranial random noise stimulation; tACS, transcranial alternating current stimulation; HD-tDCS, High Definition transcranial direct current stimulation; TE, Estimate of treatment effect (Hedge´s g; effect size); seTE, Standard error of treatment estimate; SMD, Standardised Mean Difference; CI, confidence interval.

## Figure S4

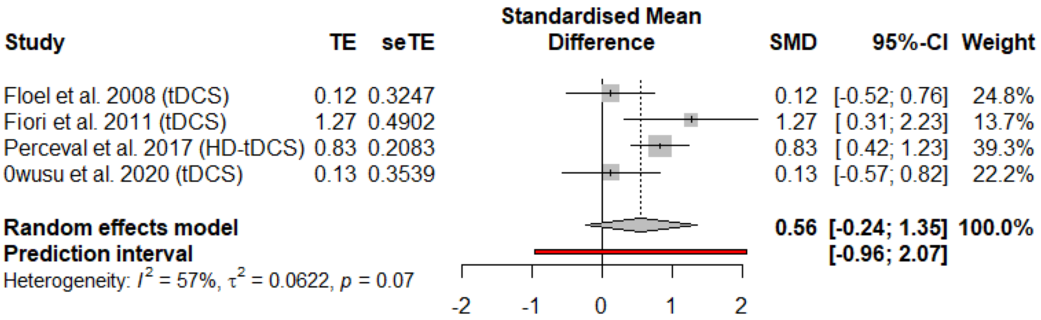
*Sensitivity analyses for response times measurements with an r = .4 for the within-subject design studies.*



*Note:* Abbreviations: tDCS, transcranial direct current stimulation; TRNS, transcranial random noise stimulation; tACS, transcranial alternating current stimulation; HD-tDCS, High-Definition transcranial direct current stimulation; TE, Estimate of treatment effect (Hedge´s g; effect size); seTE, Standard error of treatment estimate; SMD, Standardised Mean Difference; CI, confidence interval.

## Figure S5

*Sensitivity analyses for response times effect sizes with an r = .8 for the within-subject design studies.*

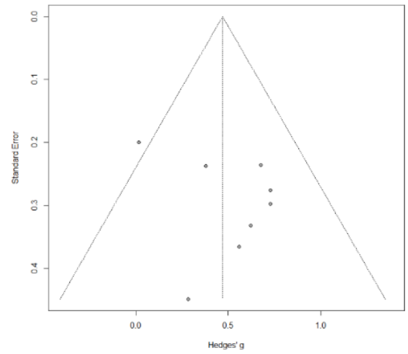


*Note:* Abbreviations: tDCS, transcranial direct current stimulation; TRNS, transcranial random noise stimulation; tACS, transcranial alternating current stimulation; HD-tDCS, High-Definition transcranial direct current stimulation; TE, Estimate of treatment effect (Hedge´s g; effect size); seTE, Standard error of treatment estimate; SMD, Standardised Mean Difference; CI, confidence interval.

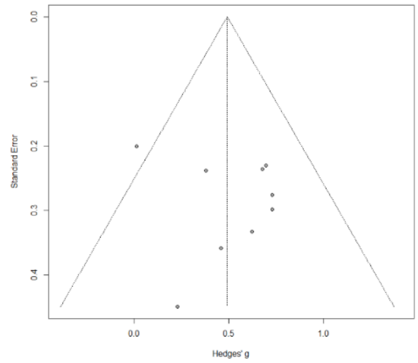
**Figure S6**

*Funnel plot of publication bias of accuracy measures:*

*Without studies with multiple stimulation sessions*



*With an r = .4 for the within-subject design studies.*



*r = .8 for the within-subject design studies.*

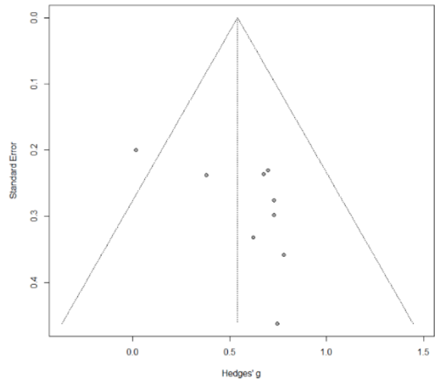
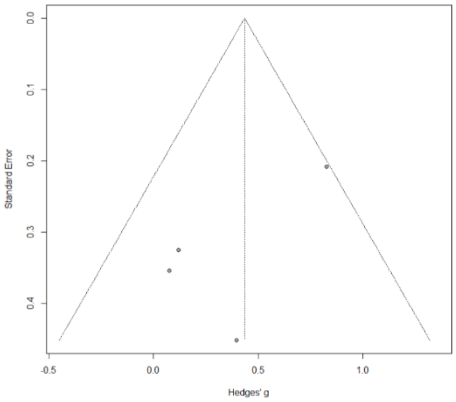


**Figure S7.**

*Funnel plot of publication bias of response times effect sizes:*

*r = .4 for the within-subject design studies.*



*r = .8 for the within-subject design studies.*