UNIVERSIDAD DE MURCIA

ESCUELA INTERNACIONAL DE DOCTORADO

TESIS DOCTORAL

Modulation of visual attention processes by noninvasive electrical brain stimulation

Modulación de procesos de atención visual mediante estimulación eléctrica cerebral no invasiva

D. Víctor Martínez Pérez 2022

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Autor: D. Víctor Martínez Pérez 2022

Directores: D. Luis J Fuentes Melero, y D. Guillermo Campoy Menéndez

UNIVERSIDAD DE
MURCIA

DECLARACIÓN DE AUTORÍA Y ORIGINALIDAD
DE LA TESIS PRESENTADA EN MODALIDAD DE COMPENDIO O ARTÍCULOS PARA OBTENER EL TÍTULO DE DOCTOR
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D./Dña. Víctor Martínez Pérez

doctorando del Programa de Doctorado en

Doctorado en Psicología

de la Escuela Internacional de Doctorado de la Universidad Murcia, como autor/a de la tesis presentada para la obtención del título de Doctor y titulada:

Modulación de procesos de atención visual mediante estimulación eléctrica cerebral no invasiva

y dirigida por,

D./Dña. Luis José Fuentes Melero

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A Kira

Title

Modulation of visual attention processes by noninvasive electrical brain stimulation

Abstract

Non-invasive transcranial stimulation (tES) is a brain stimulation technique capable of modulating cortical excitability that allows linking cognitive processes and brain structures in a causal relationship. In this doctoral thesis project, we propose a series of five experimental studies on different processes related to visual attention. Here we will employ different variants of tES (direct current and alternating current). These studies are based on the model of three attentional networks proposed by Michael Posner and aim to better characterize these networks by complementing it with more recent research paradigms such as inhibitory tagging (study 1), the self-attentional network (study 2), vigilance components (study 3), chronotypes (study 4), attentional oscillations (study 4) and mind-wandering (study 4; study 5 Under Review in Sup. Mat.).

Keywords

Visual attention, vigilance, inhibitory tagging, chronotype, self-attentional network, mind-wandering

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Abbreviations

DLPFC	Dorsolateral Prefrontal Cortex
EEG	Electroencephalography
HD	High Definition
IOR	Inhibition of Return
IT	Inhibitory Tagging
MCT	Mackworth Clock Test
MW	Mind-wandering
NIBS	Non-invasive Brain Stimulation
pSTS	posterior Superior temporal sulcus
PVT	Psychomotor Vigilance Task
RT	Reaction Times
SART	Sustained Attention to Response Task
SPE	Self-Prioritization Effects
SOA	Stimulus Onset Asynchrony
tACS	transcranial Alternating Current Stimulation
tES	transcranial Electrical Stimulation
tDCS	transcranial Direct Current Stimulation
tRNS	transcranial Random Noise Stimulation
VMPFC	Ventromedial Prefrontal Cortex

Introduction

> *"Everyone knows what attention is" (James, 1890) is one of the most popular quotes from William James and certainly the most famous statement about human attention. We argue, however, that the overuse and popularity of this statement in cognitive research has been detrimental to progress – that in fact, no one knows what attention is* (Hommel et al., 2019, p. 1).

From the time of William James to the present day, the concept of attention has been used to study a wide range of heterogeneous aspects of cognition. Therefore, the report by Hommel et al., (2019) promotes abandoning the pursuit of a unitary definition of the concept and focusing on the subset of processes and mechanisms that have traditionally been collected under the academic umbrella of the term "attention". In line with that contention, it is now well accepted that attention is no longer considered as a unitary phenomenon, but a cognitive system composed of different neural networks that perform specific functions (Posner & Petersen, 1990; Raz & Buhle, 2006). Certainly, the model that best gathers and combines different sub-aspects of attention is that proposed by Michael Posner from a cognitive neuroscience approach. Posner's model of attentional networks (Posner & Petersen, 1990) conceives of attention as a modular organic system composed of three integrated neural networks: the alerting network, the orienting network, and the executive attentional network (Posner & Rothbart, 2007). Briefly, these networks comprise the functions of providing the organisms with an appropriate arousal level, selecting relevant objects and/or locations, and exerting cognitive control (Posner & Fan, 2008). **The alerting network** would be involved in producing and maintaining the optimal state of alert, which prepares the individual to perceive or respond to a target at any given moment. This attentional function would involve the frontal and parietal cortex, especially those of the right hemisphere, and the norepinephrine projections they receive from the locus coeruleus. **The orienting network** would be involved in locating relevant objects in space, orienting sensory receptors to those locations, and filtering out irrelevant information that might compete for attention. The brain structures involved would be the parietal cortex and the temporoparietal junction, the frontal eye fields, and the superior colliculi. And the main neurotransmitter involved in these processes would be acetylcholine. **The executive attentional network** would be involved in what has come to be referred to as executive control, namely the control of action in such a way that it conforms to certain goals. This attentional function would be sustained mainly by the dopaminergic system, and brain structures such as the prefrontal cortex, the anterior cingulate cortex, and the basal ganglia.

An integrative view of the study of attention is to combine Posner's model of the three attentional networks with the network model of Corbetta and Shulman (2002), which considers that attention can be directed top-down by our goals, or bottom-up by the stimuli of the environment itself. Thus, we can consider that each of the three functions (alerting, orienting and executive control) can occur voluntarily or internally (top-down) or involuntarily and externally (bottom-up).

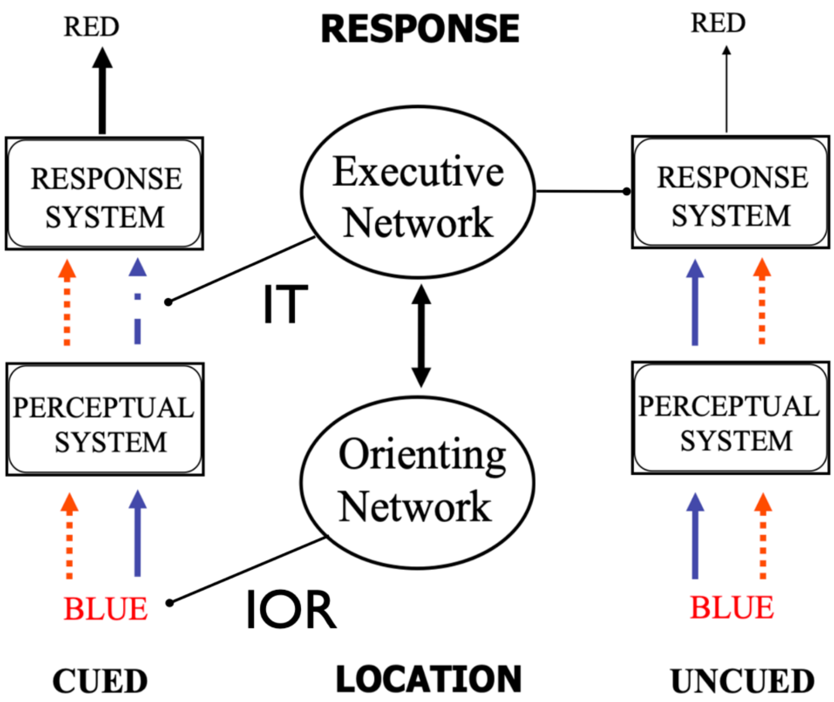
In this research project, taking as a starting point the Posner's (Posner & Petersen, 1990) model in conjunction with the Corbetta's model (Corbetta & Shulman, 2002), we will focus on modulation of visual attention processes by noninvasive electrical brain stimulation. Of special interest for the present thesis, these processes would refer to inhibitory mechanisms of the orienting network (inhibitory tagging mechanism in inhibition of return), the self-attentional network, and vigilant attention. In the following sections, the reader is introduced to concepts related to these processes.

Inhibitory Tagging in Inhibition of Return

It has been shown that the three attentional networks described by Posner interact under certain circumstances (Fan et al., 2002). One evidence of this comes from the use of an inhibition of return procedure combined with tasks that are thought to tap different information processing. IOR has been mostly studied in a cue-target paradigm with peripheral cues anticipating the forthcoming target. When the target is located and the previously cued location, reaction times (RTs) are longer than if the target is presented at the uncued location. Targets at the cued location would occur in half of trials (valid trials) whereas they occur at the uncued location in the other half (invalid trials). Thus, in the IOR procedure, the classical advantage of valid versus invalid trials (the validity effect) turns into a disadvantage when the peripheral cue is uninformative, and the time elapsed between the appearance of the cue and the target (stimulus onset asynchrony, SOA) is longer than 300 (Klein, 2000). Fuentes and cols (Fuentes, 1999; Fuentes et al., 2000; Langley et al., 2005; Vivas et al., 2003, 2007; Vivas & Fuentes, 2001) asked about the fate of stimuli that are presented to a location subject to IOR and they claimed that ongoing processing of stimuli at locations subject to IOR is strikingly modulated. For instance, Fuentes et al. (1999) combined the cuing procedure with semantic priming and flanker tasks to figure out how the processing of stimuli was affected at a location subject to IOR (cued location). The pattern of results they found was as follows. For stimuli at the location not subjected to IOR (uncued location), the typical semantic priming and flanker interference effects were observed. By contrast, for stimuli at the cued (inhibited) location, semantically related stimuli and congruent flankers yielded longer RTs than semantically unrelated and incongruent ones. That is, semantic processing was not compromised, but the access of related/congruent targets to the response was inhibited. Fuentes and cols. (Fuentes et al., 2000) went further to address the interaction between the orienting and executive networks by combining the IOR procedure (orienting) with the Stroop task (executive). At the cued location the Stroop interference observed in the incongruent condition was reduced (Vivas & Fuentes, 2001; Experiment 1) or even eliminated (Vivas and Fuentes, 2001; Experiment 2) in comparison to when the Stroop stimuli were presented at the uncued location. The authors attributed such reduction in the Stroop effect to an inhibitory tagging (IT) mechanism acting in locations subjected to IOR which would inhibit the access of the task-irrelevant but prepotent dimension of the Stroop stimuli (the word) to the response system, indirectly facilitating responses to the task-relevant dimension, the color, and consequently reducing the Stroop effect. In the second experiment, Vivas and Fuentes (2001) used a Stroop-like task to trace the time course of the orienting x executive interaction. The elimination of the Stroop interference effect at the cued location, the hallmark of IT, occurred with 250 ms word-color SOA, but the Stroop interference effect reappeared and was similar to that observed at the uncued location with longer intervals. On the basis of the aforementioned studies, the authors concluded that IT was temporarily acting in IOR by inhibiting the access of activated representations of cued stimuli to the response system. Chen et al. (2006) further demonstrated that was the left dorsolateral prefrontal cortex the brain area that was involved in IT. In **Figure 1** Fuentes (2004) illustrates the aforementioned orienting × executive attention interaction.

Figure 1

The Fuentes' (2004) model. Arrows connecting the stimulus with perception and response stages indicate the coding of Stroop stimulus dimensions, color and word, being the former the weaker (dotted lines) although task-relevant dimension, and the latter the stronger (solid lines) although task-irrelevant dimension. Response RED (the stimulus color) would be thicker (quicker) at the cued than at the uncued (slower), due to IT indirectly facilitating responses to incongruent stimuli at that location (Figure extracted from Fuentes, 2004).



Fuentes (2004) accounted for such interaction in the following terms: "*The parietal lobe might contain a map of locations where the cued location might have been inhibited. Thus, via inhibitory links with the superior colliculus, neither attention nor the eyes are facilitated to move in that direction. The net result is longer manual and/or saccades responses to the cued location (IOR effect). Concurrently, the parietal cortex might* *translate the attention/oculomotor bias in subcortical structures into a signal to those areas concerned with response selection (the executive network). Those areas, then, would inhibit the prepotent attribute of the stimulus, the word meaning, interrupting its access to the response system. The net result is an indirect facilitation in color responses, and therefore a reduction in Stroop interference (IT effect).*" (p. 51).

Self-attentional network

The concept of self has occupied a central place in the development of cognitive sciences. Findings within the field of attention are particularly noteworthy. For example, Moray's (Moray, 1959) classic experiments on selective attention proved that humans cannot avoid automatically directing our attention to an auditory source when our own name is presented there. A similar effect occurs when our name is presented in written form in the attentional blink paradigm (Shapiro et al., 1997). Likewise, an advantage in the recall of those stimuli that have previously been associated with the self has been demonstrated (Cunningham et al., 2008). Despite the manifest advantage of the self in stimulus processing, experiments using the participant's own name, face or autobiographical material, such as those previously mentioned, suffer from methodological weaknesses related to the potential confusion of the effects found associated with the self with effects of familiarity or overlearning of these stimuli. Sui, He, and Humphreys (2012) developed a procedure that eliminated these potential biases for assessing self-advantage or self-prioritization effects (SPE). In its simplest version, participants are asked to associate three geometric figures (e.g., a circle, a square, and a triangle) with themselves, their best friend, and a stranger. In the different trials of this task, pairs containing one of the 3 aforementioned geometric figures and a label ("YOU", "FRIEND" or "STRANGER") are presented and participants must decide whether that pairing is correct or incorrect (matched or not matched). The results show a self-advantage that is reflected in reaction times and error rates, which are reduced when the stimuli have been previously associated with the self, compared to those that have been associated with our best friend or a stranger. This procedure ensures that this self-advantage cannot be attributed to a familiarity or overlearning effect of the stimuli, nor to the concreteness, frequency or length of the words used (Sui et al., 2012).

At the neural level, different neuroimaging studies evidence that this distinction between self and others has its substrate in distinct brain areas in the medial prefrontal cortex (for a review, see Wagner et al., 2012 or the meta-analysis by Denny et al., 2012). Sui et al. (2013) specifically associated ventromedial prefrontal cortex (VMPFC) activation with SPE. Specifically, when participants made judgments about matching the geometric figure with the label associated with themselves the VMPFC was activated (in addition to the posterior superior temporal sulcus, pSTS), whereas in judgments about matching the geometric figure with the label associated with their best friend or stranger, brain activation was observed primarily in the dorsolateral prefrontal cortex (DLPFC). Along these lines, another source of evidence was found in a study with patients with left VMPFC lesion, who showed a lower SPE, compared to a control group (Sui et al., 2015). As a whole, the literature on this topic converges that self-relevant stimuli are processed in the MPFC, specifically in the ventral division. Thus, Humphreys and Sui (Humphreys & Sui, 2016) have proposed a Self-Attentional Network (SAN), differentiating between three components: a top-down control component associated with the DLPFC, a core of self-representation linked to the VMPFC and, finally, another component of bottom-up orientation and correlated with the previous one, which would be linked to the pSTS.

Vigilance and mind-wandering

The ability to sustain attention for long periods of time is referred to as vigilance and plays an important role in a wide variety of activities in our daily lives, as well as in certain attention-demanding jobs. It is therefore not surprising that the alerting network of Posner's model (Posner & Petersen, 1990) is also known as a vigilance network. Particularly notable and pervasive are failures in task performance over time, a phenomenon known as the vigilance decrement. This effect is evidence of the oscillatory nature of sustained attention (Clayton et al., 2015). Furthermore, vigilance have been recently dissociated in two components (Luna et al., 2018): executive vigilance, as the ability to detect infrequent critical stimuli (e.g., the Mackworth Clock Test, MCT or The Sustained Attention to Response Task, SART, see Robertson et al., 1997), and arousal vigilance, as the maintenance of an optimal level of arousal to quickly respond to the upcoming target (e.g. The Psychomotor Vigilance Task (PVT) (Lim & Dinges, 2008).

Along with the decreases in vigilance, another phenomenon is occurring across time-on-task which is known as mind-wandering (MW). MW is defined as the shifting of attention from the task's objectives to task-unrelated thoughts (Smallwood & Schooler, 2015). Recent studies shows that MW can occur spontaneously (unintentional) or deliberately (intentional) (Seli et al., 2016).

The relationship between vigilance decrement and the propensity to mind-wandering plays a crucial role in some of the most relevant current theoretical models on the functioning of attention (Thomson et al., 2015). Here, we have proposed to study in detail the interplay between these two phenomena (**Study 4** and **Study 5**).

Non-invasive brain stimulation

In the last two decades, transcranial electrical stimulation (tES) techniques have reached high heights of popularity in both academia and the popular media (Dubljević et al., 2014), as they allow causal investigations of human brain function in vivo (Filmer et al., 2020). The most widely used and prominent of these techniques is the transcranial direct current stimulation (tDCS), from less than 40 papers published in 2006 to over 1050 in 2020 (Web Of Science: search "transcranial direct current stimulation"). tDCS is a form of non-invasive brain stimulation (NIBS) capable of modulating cortical excitability by running a constant current between two electrodes (anode and cathode). This technique has been used both for basic research (see, for example Axelrod et al., 2015; Kajimura & Nomura, 2015; Luna et al., 2020) and for the development of more applied slopes, such as a treatment in the field of neurorehabilitation after stroke (Stagg & Johansen-Berg, 2013) or depression (Brunoni et al., 2014; Nord et al., 2019) and cognitive enhancement (Filmer et al., 2017; Stephens & Berryhill, 2016; Summers et al., 2016).

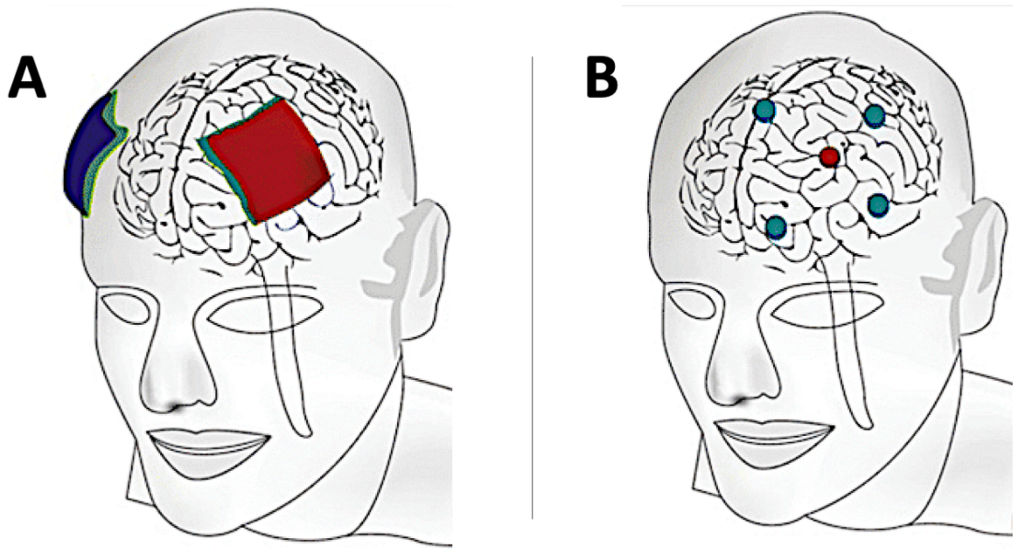
More recently, transcranial alternating current stimulation (tACS) and transcranial random noise stimulation (tRNS) have emerged as two noninvasive brain stimulation alternatives to modulate brain activity. tACS consists of the application of oscillating electrical current to modulate brain activity while tRNS consist of pulses delivered randomly across a certain range of frequencies and amplitudes. The rationale behind the use of these types of stimulation is that it is possible to restore disturbed oscillatory activity by applying alternating current externally to the brain, particularly when the applied frequency coincides with the endogenous regional synchronization that accompanies the function of interest (Santarnecchi et al., 2015; Santarnecchi et al., 2016).

Despite the effervescent and encouraging current state of the art of NIBS techniques, and tES in particular, there has been criticism regarding the validity and utility of this method, with non-trivial evidence collected that challenges reliable effects of tES on behavior (Bestmann et al., 2015; Galli et al., 2019; Horvath et al., 2015; Medina & Cason, 2017; Parkin et al., 2015). In an excellent piece of work conducted recently, Filmer et cols. (2020) highlighted the key points of controversy raised against tES. One of the most important issues could be summarized as poor experimental designs, which includes studies with insufficient control conditions, low samples sizes and the use of non-sensitive performance measures. Another important point of controversy is the lack of focality of tES compared to TMS, although the new HD-tES devices improve this issue considerably (see **Figure 2**). Finally, the most significant adverse point, and the one that occupies the bulk of this doctoral thesis, is the inter-individual variability shown in response to tES which in turn is related to issues of replicability. In the words of the authors of the aforementioned work: *"If we can understand why tDCS modulations of behaviour varies between individuals, then predictions can be made as to which subjects or patients will show the greatest effects of stimulation."* (Filmer et al., 2020, p. 7)

In the studies that comprise this doctoral thesis, we have emphasized overcoming most of these weaknesses of tES studies. Thus, our studies have improved the focality by using high definition (HD) tES (**Study 1**, **Study 2**, **Study 3**, and **Study 5**). We also have improved experimental control and designs of previous studies (**Study 2**, **Study 3,** and **Study 5**) and we have approached the field of individual differences and how they can be determinant for understanding the effects of neuromodulation on attention (**Study 3** and **Study 5**).

Figure 2

Comparison between conventional tES (A) and HD-tES (B) montages. Adapted from Ling et al. (2020)



Objectives

The general objective of this doctoral thesis was to better characterize how attention works through different experimental manipulations based on neuromodulation techniques by tES (tDCS and tACS). Taking as a starting point the theoretical model of Michael Poster (Posner & Petersen, 1990), we have addressed different questions about the functioning of the three attentional networks and their interactions. In **Study 1** (Martínez-Pérez et al., 2019), we began by asking about the functioning of the orientating network in interaction with the executive network, and more in depth, about a phenomenon that occurs when we process elements at a location subject to inhibition of return: the inhibitory tagging mechanist suggested by Fuentes and colleagues (Fuentes, 1999; Fuentes et al., 2000; Langley et al., 2005; Vivas et al., 2003; Vivas & Fuentes, 2001). This study had a threefold objective: we asked whether IT is also applied to ongoing emotional processing, to determine the emergence and development of IT in emotional conflict tasks, and whether the left DLPFC plays a causal role in IT using HD-tDCS. **Study 2** (Martínez-Pérez, Campoy, et al., 2020) was related to the executive network, namely what Glyn Humphreys and collaborators called the Self-Attentional network (Humphreys & Sui, 2016) an integrative theoretical framework for understanding the self-prioritization effects (SPE) that proposes that the ventromedial prefrontal cortex (VMPFC) and dorsolateral prefrontal cortex (DLPFC) are responsible for processing self- and other-related stimuli, respectively. Here our objectives were to study whether anodal and cathodal stimulation over the VMPFC or the DLPFC modulates the SPE, or in other words, we wanted to test the causal involvement of DLPFC/VMPFC in the processing of self-/others- related stimuli. **Study 3**, **Study 4,** and **Study 5** were related to the alerting network, and especially with what happens when the tasks require attention to be kept across time on task, i.e., sustained attention or vigilance. Here we turned the approach to the neuromodulation studies upside down, and we focused on the role of individual differences in predicting the effects of tES on cognition. In **Study 3** (Martínez-Pérez et al., 2022), we made use of the results of a previous work about chronotypes published by our research group (Martínez-Pérez, Palmero, et al., 2020) to assess the role of alpha and theta oscillations on sustained attention (vigilance) tasks. Our objectives were to investigate whether two types of vigilance (arousal and executive, see Luna et al., 2018) were causally related to theta and alpha rhythms by applying HD-tACS to the DLPFC. Here we also controlled for the differences in arousal of the participants by classifying them by chronotypes. In this manner, we tested intermediate-types at the time of day when their arousal level was deemed to be optimal and evening-types at the time of day when their arousal level was expected to be low. **Study 4** and **Study 5** are concerned with two phenomena that occur across time on task: propensity to mind-wandering and decrement of vigilance. In **Study 4** (Martínez-Pérez et al., 2021) we set out to determine whether the two components of vigilance (executive and arousal) promote different rates of mind-wandering, and whether each type of mind-wandering is differentially affected as a function of decreasing vigilance with time-on-task, depending on the vigilance component involved. Finally, the objective of **Study 5** (Martínez-Pérez et al., under review) was to dissociate mind-wandering and vigilance decrement by two different manipulations: we switched task demands (low vs high) and applied online HD-tDCS over left DLPFC (anodal vs sham).

Conclusions

Increasing our understanding of how tES techniques modulate brain regions that affects attentional functions may contribute to clarifying this puzzling question that cognitive neuroscience researchers have been asking for decades about what attention means. A cornerstone of tES studies is that allow causal link between neural networks and attentional processes as has been reflected in the development of this workpiece. This neuroscience research approach based on the search for causality has also allowed us to dissociate different aspects in the interaction of the attentional networks such as IT in IOR procedures, different types of sustained attention or vigilance: arousal and executive, including phenomena such as vigilance decrement from mind-wandering states. Along this journey we have overcome some methodological weaknesses that this field of research had in its early stages, and we have integrated critical issues such as the study of individual differences to understand how tES (in its different variants tACS and tDCS) affects individuals who present differences in their baseline or "starting point".

The more detailed conclusions that can be drawn from each of the studies that constitute this doctoral thesis are detailed below.

- IT also modulates ongoing emotional processing, demonstrated by the use of emotion laden stimuli as it is the case with cognitive tasks (Flanker, Stroop and Semantic primming) (**Study 1**).
- The signature of IT is the reduction in conflict effect which appears just with the 250 ms prime-target SOA, neither earlier nor later than that temporal interval (**Study 1**).
- A causal role of the left-DLPFC in IT have been found, irrespective of whether processing involves emotional or cognitive conflict (**Study 1**).
- Inhibitory mechanisms that rely on different attention networks interact in a cooperative way to favor attentional allocation to novel unexplored objects/locations, which suggests that search for novelty may be a pervasive characteristic of the attention system (see also Chen et al., 2010) (**Study 1**).
- Self-bias occurs in the perceptual domain using the shape-label matching paradigm, replicating previous studies (Sui et al., 2012, 2013, 2015). Specifically, we found a large SPE for both RT and accuracy data (**Study 2**).
- We found that HD-tDCS over VMPFC/DLPFC failed to selectively modulate the processing of self-/other-related stimuli which suggests that other areas involved in attention to social relevant stimuli are involved (e.g., the LpSTS) (**Study 2**).

- The frontal area plays a causal role in conflict resolution, since cathodal stimulation over the DLPFC, which is supposed to inhibit cortical activity, led to a drop-off in performance (**Study 1 and Study 2**).
- We supported the dissociation of two components of vigilance, one arousal component characteristic of monotonous tasks such as the PVT, and an executive component characteristic of cognitive demanding tasks such as the SART (**Study 3 and Study 4**).
- We showed the oscillatory nature of attention: both theta- and alpha-tACS improved arousal vigilance in the psychomotor vigilance task (PVT), whereas alpha-tACS, but not theta-tACS, improved executive vigilance in the sustained attention to response task (SART) (**Study 3**).
- Propensity to mind-wander and vigilance decrement are two pervasive phenomenon that usually occurs when people are required to perform certain activities for fairly long periods of time (**Study 4 and Study 5**).
- We found different patterns of intentional and unintentional mind-wandering (**Study 4 and Study 5**). Intentional mind-wandering occurs mainly in arousal tasks in which propensity to mind-wander has little impact on task performance. However, unintentional mind-wandering occurs mainly in executive tasks as a result of a failure of cognitive control (**Study 4**),
- The resource-control theory (Thomson et al., 2015) can be extended to account for the pattern and type of mind-wandering to be expected when people perform vigilance tasks, and differs both in the demands on cognitive control and in the type of vigilance component involved (**Study 4 and Study 5**).
- Vigilance decrement and mind-wandering do not appear to be as dependent as previously assumed. Instead, they resemble a sort of epiphenomenon (**Study 5**).

- Although the role of alpha oscillations on vigilant attention remains ambiguous, our data showed for the first time that individual differences in the alpha band at rest may influence propensity for MW when anodal HD-tDCS was applied over the l-DLPFC (**Study 5**).
- We highlighted the relevance of considering individual differences in pre-existing excitation/inhibition baseline levels for predicting tES effects on cognition (**Study 3 and Study 5**).

References

Axelrod, V., Rees, G., Lavidor, M., & Bar, M. (2015). Increasing propensity to mind-wander with transcranial direct current stimulation. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(11), 3314-3319. https://doi.org/10.1073/pnas.1421435112

Bestmann, S., de Berker, A. O., & Bonaiuto, J. (2015). Understanding the behavioural consequences of noninvasive brain stimulation. *Trends in Cognitive Sciences*, *19*(1), 13-20. https://doi.org/10.1016/j.tics.2014.10.003

Brunoni, A. R., Zanao, T. A., Vanderhasselt, M.-A., Valiengo, L., de Oliveira, J. F., Boggio, P. S., Lotufo, P. A., Benseñor, I. M., & Fregni, F. (2014). Enhancement of affective processing induced by bifrontal transcranial direct current stimulation in patients with major depression. *Neuromodulation: Journal of the International Neuromodulation Society*, *17*(2), 138-142. https://doi.org/10.1111/ner.12080

Chen, Q., Fuentes, L. J., & Zhou, X. (2010). Biasing the organism for novelty: A pervasive property of the attention system. *Human Brain Mapping*, *31*(8), 1146-1156. https://doi.org/10.1002/hbm.20924

Chen, Q., Wei, P., & Zhou, X. (2006). Distinct Neural Correlates for Resolving Stroop Conflict at Inhibited and Noninhibited Locations in Inhibition of Return. *Journal of Cognitive Neuroscience*, *18*(11), 1937-1946. https://doi.org/10.1162/jocn.2006.18.11.1937

Clayton, M. S., Yeung, N., & Cohen Kadosh, R. (2015). The roles of cortical oscillations in sustained attention. *Trends in Cognitive Sciences*, *19*(4), 188-195. https://doi.org/10.1016/j.tics.2015.02.004

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), Art. 3. https://doi.org/10.1038/nrn755

Cunningham, S. J., Turk, D. J., Macdonald, L. M., & Neil Macrae, C. (2008). Yours or mine? Ownership and memory. *Consciousness and Cognition*, *17*(1), 312-318. https://doi.org/10.1016/j.concog.2007.04.003

Denny, B. T., Kober, H., Wager, T. D., & Ochsner, K. N. (2012). A Meta-analysis of Functional Neuroimaging Studies of Self- and Other Judgments Reveals a Spatial Gradient for Mentalizing in Medial Prefrontal Cortex. *Journal of Cognitive Neuroscience*, *24*(8), 1742-1752. https://doi.org/10.1162/jocn_a_00233

Dubljević, V., Saigle, V., & Racine, E. (2014). The Rising Tide of tDCS in the Media and Academic Literature. *Neuron*, *82*(4), 731-736. https://doi.org/10.1016/j.neuron.2014.05.003

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the Efficiency and Independence of Attentional Networks. *Journal of Cognitive Neuroscience*, *14*(3), 340-347. https://doi.org/10.1162/089892902317361886

Filmer, H. L., Lyons, M., Mattingley, J. B., & Dux, P. E. (2017). Anodal tDCS applied during multitasking training leads to transferable performance gains. *Scientific Reports*, *7*(1), 12988. https://doi.org/10.1038/s41598-017-13075-y

Filmer, H. L., Mattingley, J. B., & Dux, P. E. (2020). Modulating brain activity and behaviour with tDCS: Rumours of its death have been greatly exaggerated. *Cortex*, *123*, 141-151. https://doi.org/10.1016/j.cortex.2019.10.006

Fuentes, L. J. (1999). Inhibitory Tagging of Stimulus Properties in Inhibition of Return: Effects on Semantic Priming and Flanker Interference. *The Quarterly Journal of*

Experimental Psychology Section A, *52*(1), 149-164. https://doi.org/10.1080/713755797

Fuentes, L. J. (2004). Inhibitory processing in the attentional networks. In M. I. Posner (Ed.), *Cognitive neuroscience of attention*, (pp. 45-55). New York: Guilford Press.

Fuentes, L. J., Boucart, M., Vivas, A. B., Alvarez, R., & Zimmerman, M. A. (2000). Inhibitory tagging in inhibition of return is affected in schizophrenia: Evidence from the Stroop task. *Neuropsychology*, *14*, 134-140. https://doi.org/10.1037/0894-4105.14.1.134

Galli, G., Vadillo, M. A., Sirota, M., Feurra, M., & Medvedeva, A. (2019). A systematic review and meta-analysis of the effects of transcranial direct current stimulation (tDCS) on episodic memory. *Brain Stimulation*, *12*(2), 231-241. https://doi.org/10.1016/j.brs.2018.11.008

Hommel, B., Chapman, C. S., Cisek, P., Neyedli, H. F., Song, J.-H., & Welsh, T. N. (2019). No one knows what attention is. *Attention, Perception, & Psychophysics*, *81*(7), 2288-2303. https://doi.org/10.3758/s13414-019-01846-w

Horvath, J. C., Forte, J. D., & Carter, O. (2015). Quantitative Review Finds No Evidence of Cognitive Effects in Healthy Populations From Single-session Transcranial Direct Current Stimulation (tDCS). *Brain Stimulation*, *8*(3), 535-550. https://doi.org/10.1016/j.brs.2015.01.400

Humphreys, G. W., & Sui, J. (2016). Attentional control and the self: The Self-Attention Network (SAN). *Cognitive Neuroscience*, *7*(1-4), 5-17. https://doi.org/10.1080/17588928.2015.1044427

Kajimura, S., & Nomura, M. (2015). Decreasing propensity to mind-wander with transcranial direct current stimulation. *Neuropsychologia*, *75*, 533-537.

https://doi.org/10.1016/j.neuropsychologia.2015.07.013

Klein, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, *4*(4), 138-147. https://doi.org/10.1016/S1364-6613(00)01452-2

Langley, L. K., Vivas, A. B., Fuentes, L. J., & Bagne, A. G. (2005). Differential Age Effects on Attention-Based Inhibition: Inhibitory Tagging and Inhibition of Return. *Psychology and Aging*, *20*, 356-360. https://doi.org/10.1037/0882-7974.20.2.356

Lim, J., & Dinges, D. F. (2008). Sleep deprivation and vigilant attention. En *Molecular and biophysical mechanisms of arousal, alertness, and attention* (pp. 305-322). Blackwell Publishing.

Ling, S., Raine, A., Choy, O., & Hamilton, R. (2020). Effects of prefrontal cortical stimulation on aggressive and antisocial behavior: A double-blind, stratified, randomized, sham-controlled, parallel-group trial. *Journal of Experimental Criminology*, *16*(3), 367-387. https://doi.org/10.1007/s11292-020-09427-w

Luna, F. G., Marino, J., Roca, J., & Lupiáñez, J. (2018). Executive and arousal vigilance decrement in the context of the attentional networks: The ANTI-Vea task. *Journal of Neuroscience Methods*, *306*, 77-87. https://doi.org/10.1016/j.jneumeth.2018.05.011

Luna, F. G., Román-Caballero, R., Barttfeld, P., Lupiáñez, J., & Martín-Arévalo, E. (2020). A High-Definition tDCS and EEG study on attention and vigilance: Brain stimulation mitigates the executive but not the arousal vigilance decrement. *Neuropsychologia*, *142*, 107447. https://doi.org/10.1016/j.neuropsychologia.2020.107447

Martínez-Pérez, V., Baños, D., Andreu, A., Tortajada, M., Palmero, L. B., Campoy, G., & Fuentes, L. J. (2021). Propensity to intentional and unintentional mind-wandering differs in arousal and executive vigilance tasks. *PLOS ONE*, *16*(10), e0258734. https://doi.org/10.1371/journal.pone.0258734

Martínez-Pérez, V., Campoy, G., Palmero, L. B., & Fuentes, L. J. (2020). Examining the Dorsolateral and Ventromedial Prefrontal Cortex Involvement in the Self-Attention Network: A Randomized, Sham-Controlled, Parallel Group, Double-Blind, and Multichannel HD-tDCS Study. *Frontiers in Neuroscience*, *14*. https://www.frontiersin.org/articles/10.3389/fnins.2020.00683

Martínez-Pérez, V., Castillo, A., Sánchez-Pérez, N., Vivas, A. B., Campoy, G., & Fuentes, L. J. (2019). Time course of the inhibitory tagging effect in ongoing emotional processing. A HD-tDCS study. *Neuropsychologia*, *135*, 107242. https://doi.org/10.1016/j.neuropsychologia.2019.107242

Martínez-Pérez, V., Palmero, L. B., Campoy, G., & Fuentes, L. J. (2020). The role of chronotype in the interaction between the alerting and the executive control networks. *Scientific Reports*, *10*(1), 11901. https://doi.org/10.1038/s41598-020-68755-z

Martínez-Pérez, V., Tortajada, M., Palmero, L. B., Campoy, G., & Fuentes, L. J. (2022). Effects of transcranial alternating current stimulation over right-DLPFC on vigilance tasks depend on the arousal level. *Scientific Reports*, *12*(1), Art. 1. https://doi.org/10.1038/s41598-021-04607-8

Medina, J., & Cason, S. (2017). No evidential value in samples of transcranial direct current stimulation (tDCS) studies of cognition and working memory in healthy populations. *Cortex*, *94*, 131-141. https://doi.org/10.1016/j.cortex.2017.06.021

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, *11*(1), 56-60. https://doi.org/10.1080/17470215908416289

Nord, C. L., Halahakoon, D. C., Limbachya, T., Charpentier, C., Lally, N., Walsh, V., Leibowitz, J., Pilling, S., & Roiser, J. P. (2019). Neural predictors of treatment response to brain stimulation and psychological therapy in depression: A double-blind randomized controlled trial. *Neuropsychopharmacology*, *44*(9), Art. 9. https://doi.org/10.1038/s41386-019-0401-0

Parkin, B. L., Ekhtiari, H., & Walsh, V. F. (2015). Non-invasive Human Brain Stimulation in Cognitive Neuroscience: A Primer. *Neuron*, *87*(5), 932-945. https://doi.org/10.1016/j.neuron.2015.07.032

Posner, M. I., & Fan, J. (2008). Attention as an organ system. En J. R. Pomerantz (Ed.), *Topics in Integrative Neuroscience* (1.ª ed., pp. 31-61). Cambridge University Press. https://doi.org/10.1017/CBO9780511541681.005

Posner, M. I., & Petersen, S. E. (1990). The Attention System of the Human Brain. *Annual Review of Neuroscience*, *13*(1), 25-42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., & Rothbart, M. K. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1-23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Raz, A., & Buhle, J. (2006). Typologies of attentional networks. *Nature Reviews. Neuroscience*, *7*(5), 367-379. https://doi.org/10.1038/nrn1903

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). `Oops!': Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, *35*(6), 747-758. https://doi.org/10.1016/S0028-3932(97)00015-8

Seli, P., Risko, E. F., & Smilek, D. (2016). On the Necessity of Distinguishing Between Unintentional and Intentional Mind Wandering. *Psychological Science*, *27*(5), 685-691. https://doi.org/10.1177/0956797616634068

Shapiro, K. L., Caldwell, J., & Sorensen, R. E. (1997). Personal names and the attentional blink: A visual «cocktail party» effect. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 504-514. https://doi.org/10.1037/0096-1523.23.2.504

Smallwood, J., & Schooler, J. W. (2015). The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annual Review of Psychology*, *66*(1), 487-518. https://doi.org/10.1146/annurev-psych-010814-015331

Stagg, C., & Johansen-Berg, H. (2013). Studying the Effects of Transcranial Direct-Current Stimulation in Stroke Recovery Using Magnetic Resonance Imaging. *Frontiers in Human Neuroscience*, *7*. https://www.frontiersin.org/articles/10.3389/fnhum.2013.00857

Stephens, J. A., & Berryhill, M. E. (2016). Older Adults Improve on Everyday Tasks after Working Memory Training and Neurostimulation. *Brain Stimulation*, *9*(4), 553-559. https://doi.org/10.1016/j.brs.2016.04.001

Sui, J., Enock, F., Ralph, J., & Humphreys, G. W. (2015). Dissociating hyper and hypoself biases to a core self-representation. *Cortex*, *70*, 202-212. https://doi.org/10.1016/j.cortex.2015.04.024

Sui, J., He, X., & Humphreys, G. W. (2012). Perceptual effects of social salience: Evidence from self-prioritization effects on perceptual matching. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 1105-1117. https://doi.org/10.1037/a0029792

Sui, J., Rotshtein, P., & Humphreys, G. W. (2013). Coupling social attention to the self forms a network for personal significance. *Proceedings of the National Academy of Sciences*, *110*(19), 7607-7612. https://doi.org/10.1073/pnas.1221862110

Summers, J. J., Kang, N., & Cauraugh, J. H. (2016). Does transcranial direct current stimulation enhance cognitive and motor functions in the ageing brain? A systematic review and meta- analysis. *Ageing Research Reviews*, *25*, 42-54. https://doi.org/10.1016/j.arr.2015.11.004

Thomson, D. R., Besner, D., & Smilek, D. (2015). A resource-control account of sustained attention: Evidence from mind-wandering and vigilance paradigms. *Perspectives on psychological science*, *10*(1), 82-96.

Vivas, A. B., & Fuentes, L. J. (2001). Stroop interference is affected in inhibition of return. *Psychonomic Bulletin & Review*, *8*(2), 315-323. https://doi.org/10.3758/BF03196167

Vivas, A. B., Fuentes, L. J., Estevez, A. F., & Humphreys, G. W. (2007). Inhibitory tagging in inhibition of return: Evidence from flanker interference with multiple distractor features. *Psychonomic Bulletin & Review*, *14*(2), 320-326. https://doi.org/10.3758/BF03194071

Vivas, A. B., Humphreys, G. W., & Fuentes, L. J. (2003). Inhibitory processing following damage to the parietal lobe. *Neuropsychologia*, *41*(11), 1531-1540. https://doi.org/10.1016/S0028-3932(03)00063-0

Wagner, D. D., Haxby, J. V., & Heatherton, T. F. (2012). The representation of self and person knowledge in the medial prefrontal cortex. *WIREs Cognitive Science*, *3*(4), 451-470. https://doi.org/10.1002/wcs.1183

RESUMEN EN ESPAÑOL

Antecedentes:

La estimulación transcraneal no invasiva (tES) es una técnica de estimulación cerebral capaz de modular la excitabilidad cortical que permite vincular procesos cognitivos y estructuras cerebrales en una relación de causalidad. En este proyecto de tesis doctoral se proponen una serie de cinco estudios experimentales sobre diferentes procesos relacionados con la atención visual donde emplearemos diferentes variantes de esta técnica de neuromodulación: corriente directa o tDCS y corriente alterna o tACS, por sus siglas en inglés. Estos estudios parten del modelo de tres redes atencionales propuesto por Michael Posner y tienen como objetivo caracterizar mejor estas redes integrándolo en paradigmas de investigación más recientes como el inhibitory tagging (estudio 1), la self-attentional network (estudio 2), los componentes de vigilancia (estudio 3), el cronotipo (estudio 4), las oscilaciones de la atención (estudio 4) y el mind-wandering (estudio 5). El modelo de redes atencionales de Posner (Posner y Petersen, 1990) concibe la atención como un sistema orgánico modular compuesto por tres redes neuronales integradas: la red de alerta, la red de orientación y la red atencional ejecutiva (Posner y Rothbart, 2007). En esencia, estas redes comprenden las funciones de proporcionar a los organismos un nivel de arousal adecuado, de seleccionar objetos y/o lugares relevantes y de ejercer control cognitivo (Posner & Fan, 2008). Una visión integradora del estudio de la atención consiste en combinar el modelo de Posner de las tres redes atencionales con el modelo de redes de Corbetta y Shulman (2002), que considera que la atención puede estar dirigida de arriba abajo por nuestros objetivos, o de abajo arriba por los estímulos del propio entorno. Así, podemos considerar que cada una de las tres funciones (alerta, orientación y control ejecutivo) puede ocurrir de forma voluntaria o interna (top-down) o involuntaria y externa (bottom-up).

Objetivos:

El objetivo general de esta tesis doctoral ha sido caracterizar mejor el funcionamiento de la atención a través de diferentes manipulaciones experimentales basadas en técnicas de neuromodulación tES (tDCS y tACS). Tomando como punto de partida el modelo teórico de Michael Poster (Posner & Petersen, 1990), hemos abordado diferentes cuestiones sobre el funcionamiento de las tres redes atencionales y sus interacciones. En el Estudio 1 (Martínez-Pérez et al., 2019), comenzamos preguntándonos por el funcionamiento de la red de orientación y su interacción con la red ejecutiva. Más en profundidad, nos preguntamos por el funcionamiento de un fenómeno que ocurre cuando atendemos y procesamos elementos en una localización sujeta a inhibición de retorno: el mecanicismo de etiquetaje inhibitorio (IT) sugerido por Fuentes y colegas (Fuentes, 1999; Fuentes et al., 2000; Langley et al., 2005; Vivas et al., 2003; Vivas & Fuentes, 2001). Este estudio tenía un triple objetivo: en primer lugar, nos preguntamos si el IT también se aplica al procesamiento emocional en curso. En segundo lugar, queríamos estudiar la aparición y el curso temporal del IT en tareas de conflicto emocional. Finalmente, nos preguntamos si el DLPFC izquierdo desempeña un papel causal en el IT, para lo cual aplicamos tDCS de alta definición. El Estudio 2 (Martínez-Pérez, Campoy, et al., 2020) se relacionó con la red ejecutiva, concretamente con lo que Glyn Humphreys y colaboradores denominaron la red Self-Atencional (Humphreys & Sui, 2016), un marco teórico integrador para comprender los efectos de priorización del self (SPE) en el cual se propone que la corteza prefrontal ventromedial (VMPFC) y la corteza prefrontal dorsolateral (DLPFC) son responsables del procesamiento de estímulos relacionados con uno mismo y con los demás, respectivamente. Aquí nuestros objetivos eran estudiar si la estimulación anodal y catodal sobre el VMPFC o el DLPFC modula el SPE, en otras palabras, queríamos probar la implicación causal del DLPFC/VMPFC en el procesamiento de estímulos relacionados con uno mismo/otros. Los Estudios 3, 4 y 5 estaban relacionados con la red de alerta, y especialmente con lo que ocurre cuando las tareas requieren mantener la atención de forma sostenida a lo largo del curso de la tarea, es decir, con el fenómeno de vigilancia. Aquí cambiamos el enfoque tradicional de los estudios de neuromodulación y nos centramos en el papel que juegan de las diferencias individuales en la predicción de los efectos de la tES sobre la cognición. En el Estudio 3 (Martínez-Pérez et al., 2022), hicimos uso de los resultados de un trabajo previo sobre cronotipos llevado a cabo por nuestro grupo de investigación (Martínez-Pérez, Palmero, et al., 2020) para evaluar el papel de las oscilaciones alfa y theta en tareas de atención sostenida (vigilancia). Nuestros objetivos eran investigar si dos tipos de vigilancia (arousal y ejecutiva, ver Luna et al., 2018) estaban causalmente relacionados con los ritmos theta y alfa aplicando HD-tACS en el DLPFC. En este trabajo controlamos las diferencias en el arousal de los participantes clasificándolos por cronotipos. De este modo, evaluamos a participantes con cronotipos intermedios a la hora del día en que se consideraba que su nivel de excitación era óptimo y a los participantes con cronotipos vespertinos a la hora del día en que se esperaba que su nivel de excitación fuera bajo (por la mañana). Los Estudios 4 y 5 se centran en dos fenómenos que ocurren a lo largo del tiempo en la tarea: la propensión al mind-wandering y el decremento de la vigilancia. En el Estudio 4 (Martínez-Pérez et al., 2021) nos propusimos determinar si los dos componentes de la vigilancia (ejecutivo y de arousal) promueven diferentes tasas de mind wandering, y si cada tipo de mind wandering se ve afectado diferencialmente en función del decremento en la vigilancia con el tiempo en la tarea, dependiendo a su vez del componente de vigilancia implicado. Por último, el objetivo del Estudio 5 (Martínez-Pérez et al., en revisión) era disociar el mind wandering y el efecto de decremento de la vigilancia mediante dos manipulaciones diferentes: variar las demandas de la tarea (baja frente a alta) y aplicar HD-tDCS online sobre el DLPFC izquierdo (anodal frente a sham).

Algunas cuestiones metodológicas relevantes:

A pesar del efervescente y alentador estado actual de las técnicas estimulación eléctrica cerebral no invasiva, y de la tES en particular, ha habido importantes críticas respecto a la validez y utilidad de este método, surgiendo en los últimos años algunos estudios que cuestionan la replicabilidad y fiabilidad de los efectos de la tES sobre la cognición (Bestmann et al., 2015; Galli et al., 2019; Horvath et al., 2015; Medina & Cason, 2017; Parkin et al., 2015). En un excelente trabajo realizado recientemente, Filmer et cols. (2020) destacaron los puntos clave de controversia planteados en el uso de técnicas como la tES. Una de las cuestiones más importantes podría resumirse el uso de pobres diseños experimentales, que incluyen estudios con condiciones de control insuficientes, tamaños muestrales bajos y el uso de medidas o pruebas con baja sensibilidad. Otro punto importante de controversia es la falta de focalización de la tES en comparación con otras técnicas como la TMS. Por último, el punto adverso más significativo, y el que ocupa la mayor parte de esta tesis doctoral, es la variabilidad interindividual mostrada en la respuesta a la tES, que a su vez está relacionada con cuestiones de replicabilidad.

En los estudios que componen esta tesis doctoral, hemos hecho hincapié en superar la mayoría de estas debilidades que presentaban los estudios de tES. Así, nuestros estudios han mejorado la focalidad utilizando tES de alta definición (HD) (Estudio 1, Estudio 2, Estudio 3 y Estudio 5). También hemos mejorado el control experimental y los diseños de estudios anteriores (Estudio 2, Estudio 3 y Estudio 5) y nos hemos acercado al campo de las diferencias individuales para estudiar cómo pueden ser determinantes para entender los efectos de la neuromodulación sobre la atención (Estudio 3 y Estudio 5).

Conclusiones:

Un aspecto clave de los estudios de tES es que permiten establecer un vínculo causal entre las redes neuronales y los procesos atencionales subyacentes, como se ha reflejado en el desarrollo de esta tesis doctoral. Este enfoque de investigación en neurociencia cognitiva basado en la búsqueda de causalidad nos ha permitido también disociar diferentes aspectos sobre la interacción de las redes atencionales como el IT en procedimientos IOR, diferentes tipos de atención sostenida: vigilancia arousal vs vigilancia ejecutiva, incluyendo la distinción entre el decremento de la vigilancia frente a estados de mind wandering. A lo largo de estos trabajos se han superado algunas debilidades metodológicas que este campo de investigación presentaba en sus inicios, y se han integrado cuestiones críticas como el estudio de las diferencias individuales para comprender cómo la tES (en sus distintas variantes tACS y tDCS) afecta a individuos que presentan diferencias en su línea base o "punto de partida".

A continuación, se detallan las principales conclusiones que pueden extraerse de cada uno de los estudios que constituyen esta tesis doctoral.

- El IT también modula el procesamiento emocional en curso, demostrando que el uso de estímulos cargados emocionalmente replica los efectos encontrados en las tareas cognitivas (Flanker, Stroop y Semantic primming) (Estudio 1).
- La firma del TI es la reducción del efecto de conflicto que aparece justo con el SOA prime-target de 250 ms, ni antes ni después de ese intervalo temporal (Estudio 1).
- Se ha encontrado un papel causal de la DLPFC izquierda en el IT, independientemente de si el procesamiento implica conflicto emocional o cognitivo (Estudio 1).

- Los mecanismos inhibitorios que dependen de diferentes redes atencionales interactúan de forma cooperativa para favorecer la atención a objetos/localizaciones novedosos e inexplorados, lo que sugiere que la búsqueda de la novedad puede ser una característica omnipresente del sistema atencional (véase también Chen et al., 2010) (Estudio 1).
- El efecto de facilitación del self se produce en el dominio perceptivo utilizando el paradigma de matching task, replicando estudios previos (Sui et al., 2012, 2013, 2015). Específicamente, encontramos un incremento del SPE tanto en los tiempos de reacción como en la precisión de los participantes (Estudio 2).
- Encontramos que aplicar HD-tDCS sobre VMPFC/DLPFC no logró modular selectivamente el procesamiento de estímulos relacionados con uno mismo/otros, lo que sugiere que podría haber otras áreas involucradas en los efectos de priorización del self (por ejemplo, el LpSTS) (Estudio 2).
- El área frontal desempeña un papel causal en la resolución de conflictos, ya que la estimulación catódica sobre la DLPFC, que se supone que inhibe la actividad cortical, provocó un descenso del rendimiento (Estudio 1 y Estudio 2).
- Hemos encontrado evidencia sobre la disociación de dos componentes de la vigilancia: un componente de arousal característico de tareas monótonas como el PVT, y un componente ejecutivo característico de tareas cognitivas exigentes como el SART (Estudio 3 y Estudio 4)
- Demostramos la naturaleza oscilatoria de la atención: tanto la estimulación theta- como la estimulación alfa-tACS mejoraron la vigilancia tipo arousal en el PVT, mientras que la estimulación alfa-tACS, pero no la estimunlación theta-tACS, mejoraron la vigilancia ejecutiva en la tarea SART (Estudio 3).

- La propensión a mind wandering y el decremento de la vigilancia son dos fenómenos ubicuos que suelen ocurrir cuando se exige a las personas que realicen determinadas actividades durante periodos de tiempo prolongados (Estudio 4 y Estudio 5).
- Encontramos diferentes patrones de mind wandering intencional y no intencional (Estudio 4 y Estudio 5). El mind wandering intencional ocurriría principalmente en tareas tipo arousal en las que la propensión a este estado tiene poco impacto en el rendimiento de la tarea. Sin embargo, el mind wandering no intencional se produciría principalmente en tareas ejecutivas como resultado de un fallo en el control cognitivo (Estudio 4),
- La teoría del control de recursos (Thomson et al., 2015) puede ampliarse para dar cuenta del patrón y el tipo de vagabundeo mental que cabe esperar cuando las personas realizan tareas de vigilancia, y difiere tanto en las demandas sobre el control cognitivo como en el tipo de componente de vigilancia implicado (Estudio 4 y Estudio 5).
- El decremento de la vigilancia y la propensión a mind-wandering no parecen ser tan dependientes como se suponía anteriormente. Por el contrario, parecen una especie de epifenómeno (Estudio 5).
- Aunque el papel de las oscilaciones alfa en la atención visual sigue siendo ambiguo, nuestros datos mostraron por primera vez que las diferencias individuales en la banda alfa en reposo pueden influir en la propensión a mind wandering cuando se aplicó HD-tDCS anodal sobre el l-DLPFC (Estudio 5).
- Destacamos la importancia de considerar las diferencias individuales en los niveles basales de excitación/inhibición preexistentes para predecir los efectos de los tES sobre la cognición (Estudio 3 y Estudio 5)

Study 1: Orienting and inhibition of return: inhibitory tagging

Reference: **Martínez-Pérez, V.**, Castillo, A., Sánchez-Pérez, N., Vivas, A. B., Campoy, G., & Fuentes, L. J. (2019). Time course of the inhibitory tagging effect in ongoing emotional processing. A HD-tDCS study. *Neuropsychologia*, *135*, 107242. https://doi.org/10.1016/j.neuropsychologia.2019.107242

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Abstract: When a cueing procedure that usually triggers inhibition of return (IOR) effects is combined with tasks that tap semantic processing, or involve response-based conflict, an inhibitory tagging (IT) emerges that disrupts re- sponses to stimuli at inhibited locations. IT seems to involve the executive prefrontal cortex, mainly the left dorsolateral prefrontal cortex (DLPFC), in cognitive conflict tasks. Contrary to other inhibitory effects, IT has been observed with rather short intervals, concretely when the stimulus onset asynchrony (SOA) between the prime presented at the cued location, and the subsequent target is 250 ms. Here we asked whether IT is also applied to ongoing emotional processing, and whether the left DLPFC plays a causal role in IT using HD-tDCS. In two experiments with an emotional conflict task, we observed reduced conflict effects, the signature of IT, when the prime word was presented at the cued location, and once again when the prime-target SOA was just 250 ms. Also, the IT effect was eliminated when cathodal stimulation was applied to the left DLPFC. These findings suggest that the IT effect involves areas of the executive attention network and cooperates with IOR to favor attentional allocation to novel unexplored objects/locations, irrespective of their emotional content.

Study 2: Self-attentional network

Reference: **Martínez-Pérez, V.**, Campoy, G., Palmero, L. B., & Fuentes, L. J. (2020). Examining the dorsolateral and ventromedial prefrontal cortex involvement in the self-attention network: A randomized, sham-controlled, parallel group, double-blind, and multichannel HD-tDCS study. *Frontiers in Neuroscience*, *14*, 683. https://doi.org/10.3389/fnins.2020.00683

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Abstract: Attention and perception are strongly biased toward information about oneself compared to information about others. The self-attention network, an integrative theoretical framework for understanding the self-prioritization effects (SPE), proposes that the ventromedial prefrontal cortex (VMPFC), and the posterior superior temporal sulcus (pSTS) are the two nodes responsible for the preferential processing of self- related stimuli, which interact with the attentional control network (associated with the dorsolateral prefrontal cortex, DLPFC), responsible for processing other-related stimuli. So far, neuroimaging studies have provided considerable correlational evidence supporting the self-attention network. Here we went beyond correlational evidence by manipulating cortical activity using high-definition transcranial direct current stimulation (HD-tDCS), a non-invasive brain stimulation method. We assessed whether anodal and cathodal stimulation of the VMPFC or the DLPFC modulates the processing of self- and other-related stimuli. We used an associative unbiased learning procedure, the so-called shape-label matching task, to assess the SPE in a sample of N = 90. We accomplished to overcome different methodological weaknesses of previous studies using different multichannel montages for excitatory and inhibitory effects over both the VMPFC and the DLPFC. We found no effect of shape association for non-matching pairs, whereas

there was an effect of shape association in the matching condition. Performance (reaction times and accuracy) was better for the self association than for the other two associations, and performance for the friend association was better than for the stranger

Study 3: Oscillatory nature of sustained attention

Reference: **Martínez-Pérez, V.**, Tortajada, M., Palmero, L. B., Campoy, G., & Fuentes, L. J. (2022). Effects of transcranial alternating current stimulation over right-DLPFC on vigilance tasks depend on the arousal level. *Scientific Reports*, *12*(1), 1-10. https://doi.org/10.1038/s41598-021-04607-8

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Abstract: Current theoretical accounts on the oscillatory nature of sustained attention predict that entrainment via transcranial alternating current stimulation (tACS) at alpha and theta frequencies on specific areas of the prefrontal cortex could prevent the drops in vigilance across time-on-task. Nonetheless, most previous studies have neglected both the fact that vigilance comprises two dissociable components (i.e., arousal and executive vigilance) and the potential role of differences in arousal levels. We examined the effects of theta- and alpha-tACS over the right dorsolateral prefrontal cortex in both components of vigilance and in participants who differed in arousal level according to their chronotype and time of testing. Intermediate-types performed the vigilance tasks when their arousal level was optimal, whereas evening-types performed the vigilance tasks when their arousal levels were non- optimal. Both theta- and alpha-tACS improved arousal vigilance in the psychomotor vigilance task (PVT), whereas alpha-tACS, but not theta-tACS, improved executive vigilance in the sustained attention to response task (SART), and

counteracted the typical vigilance decrement usually observed in this task. Importantly, these stimulation effects were only found when arousal was low (i.e., with evening-types performing the tasks at their non-optimal time of day). The results support the multicomponent view of vigilance, the relevance of heeding individual differences in arousal, and the role of alpha oscillations as a long-range cortical scale synchronization mechanism that compensates the decrements in performance as a function of time-on-task by exerting and maintaining cognitive control attributed to activation of the right dorsolateral prefrontal cortex.

Study 4: Mind-wandering and vigilance task

Reference: **Martínez-Pérez, V.**, Baños, D., Andreu, A., Tortajada, M., Palmero, L. B., Campoy, G., & Fuentes, L. J. (2021). Propensity to intentional and unintentional mind-wandering differs in arousal and executive vigilance tasks. *PLoS One*, *16*(10), e0258734. https://doi.org/10.1371/journal.pone.0258734

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Abstract: We typically observe a decrement in vigilance with time-on-task, which favors the propensity for mind-wandering, i.e., the shifting of attention from the task at hand to task-unrelated thoughts. Here, we examined participants' mind-wandering, either intentional or unintentional, while performing vigilance tasks that tap different components of vigilance. Intentional mind-wandering is expected mainly when the arousal component is involved, whereas unintentional mind-wandering is expected mainly in tasks involving the executive component. The Psychomotor Vigilance Task (PVT) assessed the arousal component, whereas the Sustained Attention to Response task (SART) assessed the executive component of vigilance. The two types of mind-wandering were probed throughout task execution. The results showed that the overall rate of mind-wandering was higher in the PVT than in the SART. Intentional mind-wandering was higher with the PVT than with the SART, whereas unintentional mind-wandering was higher with the SART than with the PVT. Regarding mind-wandering as a function of vigilance decrement with time-on-task, unintentional mind-wandering in the PVT increased between blocks 1 and 2 and then stabilized, whereas a progressive increase was observed in the SART. Regarding intentional mind-wandering, a progressive increase was only observed in the SART. The differential patterns of intentional and unintentional mind-wandering in both tasks suggest that, intentional mind wandering occurs mainly in arousal tasks in which propensity to mind-wander has little impact on task performance. However, unintentional mind-wandering occurs mainly in executive tasks as a result of a failure of cognitive control, which promotes attentional resources to be diverted toward mind-wandering. These results are discussed in the context of the resource-control model of mind-wandering.

SUPPLEMENTARY MATERIAL:

Study 5: Dissociating vigilance from mind-wandering (Under Review)

Reference: **Martínez-Pérez, V.**, Andreu, A., Sandoval-Lentisco, A., Tortajada, M., Palmero, L. B., Castillo, A., Campoy, G., & Fuentes, L. J. (2022). Vigilance Decrement and Mind-Wandering: Two Sides of the Same Coin?. (Under Review). https://doi.org/10.21203/rs.3.rs-2072380/v1